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iPCMC 2024

8th International Project and Construction Management Conference

8TH INTERNATIONAL PROJECT AND CONSTRUCTION MANAGEMENT CONFERENCE

PROCEEDINGS BOOK

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YTÜ

YILDIZ TECHNICAL UNIVERSITY

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PREFACE

Welcome to Istanbul for the 8th International Project and Construction Management Conference (IPCMC), We expect this year's conference to be hosted by Yildiz Technical University with more participation than the previous conferences. The conference aims to facilitate interdisciplinary integration and international cooperation among academicians, industry professionals and researchers in the project and construction management field to share their latest research findings, experiences, and prospects. IPCMC 2024 is expected to serve as a forum especially for the early-stage researchers to discuss their research ideas, preliminary findings of their studies and develop new academic networks. Well-known keynote speakers from academia are invited to share their experiences and foresights. As a tradition of the IPCMC conferences, rewards will be delivered to the best papers. In this way, it is aimed to provide an interaction between academia and industry.

IPCMC 2024 attracted a great attention with a total of 114 full-text papers to be presented verbally. The regular increase in the number of papers in the IPCMC to date indicates the importance of project and construction management research at the international level. It can also be considered that the popularity of this year's host city, i.e., Istanbul, may have contributed to this attention. It is Istanbul's endless variety that fascinates its visitors. Istanbul is Türkiye's most developed and largest city, with the latest discoveries indicating that the history of human habitation here goes back some 400,000 years. The museums, churches, palaces, grand mosques, bazaars, and sites of natural beauty are countless.

Looking at the main topics of the conference, the most papers were written on (1) digital technologies, (2) disaster, risks and resilience, (3) organization, leadership and strategy, (4) construction methods and technology, (5) construction management and dispute resolution, (6) economical and financial management, (7) professional issues in education and practice, (8) clean energy and sustainability, (9) project management, respectively. These topics are of great importance as they highlight the current needs and trends of research society and the industry. These trends are expected to significantly guide young scholars and professionals who are at the very beginning of their research and/or working lives.

We would like to express our gratitude to Honorary Chair, Rector of YTU, Prof. Tamer Yılmaz, and co-chairs Prof. M. Talat Birgönül and Prof. Zeynep Işık for their valuable contributions to the Conference, and all the researchers who took part in the Conference Organizing, Scientific, and Reward Assessment Committees. Finally, we would like to thank 23 companies that provided financial support to the realization of the Conference. We would like to thank all the participants for their contributions to the field of project and construction management by participating in the IPCMC 2024. We sincerely hope that the academic community and industrial practitioners will continue to support us in our attempts to provide even more meaningful conferences with numerous critical idea exchanges, diverse opportunities for fruitful networking and future collaborations between the delegates.

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Yildiz Technical University, Istanbul, 06-07 June 2024

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The Role and Model of Building Inspection Systems in BIM Transformation Processes

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Abstract

Building Information Modelling (BIM) encompasses an innovative construction process used in the construction industry in cooperation with the field of architecture, engineering and construction (AEC) industry. It is seen in the literature review that BIM is not yet an actively used system for developing countries such as Turkey. One of the main reasons why BIM is not actively used in Turkey is that BIM implementation processes and existing Turkey construction implementation processes are not fully compatible in AEC. When the current project design and construction processes in Turkey are examined, although the stakeholders are independent of each other, a process is carried out under the control of a centralized system such as building inspections and municipality. However, in the current situation, there are disruptions in the process due to many reasons, such as time losses in data transfer between stakeholders, incomplete data transfer between stakeholders, and misunderstandings. It is thought that these problems can be solved by using BIM systems. Within the scope of this study, it is aimed to present a model that developing countries such as Turkey can use and supervise not only in the project design phase or only in the implementation phase but also in all construction processes of a building. Within the scope of the study, firstly the role and information flow of the building inspection system in the project design processes will be modelled and then its integration with the BIM system will be modelled. In modelling, data transfer between stakeholders will be modelled with IDM (Information Delivery Manual) method and the content of the data to be transferred with MVD (Model View Definition) method will be determined. As a result of the study, the role and model of building inspections in the BIM integration process will be determined. The study is unique in terms of a new process model integrated with BIM in which the existing project approval process will be preserved.

Keywords: *BIM, building inspection system, IDM, MVD, Turkish construction industry.*

Introduction

Building inspection systems (BIS), which are part of the Turkish construction sector, involve a multi-stakeholder process that requires the evaluation of different types of projects together. However, using traditional methods, there are many problems in the process due to people, file sharing and the lack of an established standardization.

Within the scope of this study, it is aimed to develop solutions by using Building Information Modeling (BIM) processes to identify and solve the problems existing in the BIS in Turkey. In the international literature review conducted to identify the deficiencies in the BIS in Turkey, it has been determined, that there are differences between the BIS systems implemented in foreign countries and the building inspection system being implemented in Turkey. BIS vary from country to country or according to the workflows adopted by local governments. Within the scope of this study, a BIM model has been developed in accordance with the workflow models of BIS in Turkey, which is one of the developing countries.

Developments related to (BIS) in Turkey have been experienced after natural disasters and the devastating effects of these disasters (Demir, 2017). BIS processes currently used, After the Constitutional Court annulled the Decree Law No. 595, a new era started with the Law No. 4708 on Law on Building Inspection (LoBIS) published in the Official Gazette on 13.07.2001 in order to close the gaps in the inspection system and to prevent the problems arising from the deficiencies in the previously implemented systems (Erdal, 2022; Özkan, 2005; Taşcı, 2017). The purpose of the 4708 LoBIS is to ensure the safety of life and property and to ensure that buildings are built in accordance with their projects and in accordance with certain standards. In addition, it is to ensure the supervision of the projects during implementation through building supervision organizations and to regulate the procedures and principles regarding building supervision (Boysal, 2022; Doğan, 2013; Erdal, 2022; Güleş, 2019; Güncü, 2020; Karahan, 2008; Karaoğlu, 2011; Kural, 2015). With this law, it has been concluded that the inspection system should be institutionalized. It is aimed to establish independent, experienced organizations in order to effectively carry out the inspection of buildings from the project stage to the end of the implementation phase from a single source (Erdal, 2022; Karaoğlu, 2011). With 4708 LoBIS, inspections are carried out at all stages from the design stage to the end of the construction process. The examination and approval of the projects of the building, the stages of obtaining the license of the approved projects and the process of identifying the structures that do not comply with the license and taking the necessary actions are the way this system works (Engin, 2022; Erdal, 2022; Karaoğlu, 2011; Taşcı, 2017).

In 2018, with the implementation of some changes made in LoBIS as of 01.01.2019, the organization that will carry out the inspection works of the buildings started to be determined electronically. Thus, instead of the building owners being able to do business with the inspection institution of their choice, the works are distributed electronically through the central system. However, these laws and regulations have not been sufficient to solve the problems in BIS processes in the current situation. There are still problems arising from individuals and institutions, file sharing and problems arising from incomplete or unclear data in the file content. Within the scope of this study, it is proposed to develop an IDM method for solving the problems existing in BIS processes with BIM processes.

Methodology

This study particularly focuses on the scale of the Turkish construction industry and aims to develop a process integrated with BIM to solve problems experienced in BIS systems that are actively involved in the Turkish construction industry. The research framework consists of three successive stages: First, it aimed to identify the workflow processes currently in use. Then, BIM-IDM modeling processes illustrating the data flow processes were prepared to assess the data flow between individuals, organizations and stakeholders. Finally, an IDM model was developed for BIS systems in the Turkish construction industry. This is a pilot study scenario. The accuracy of the model is out of scope. The model can be improved and adjusted for future studies.

BIS Process in Turkish Construction Industry

When starting to work on the preparation of concept projects, which is determined as the first stage of the architectural project stages in the Turkish construction sector, the zoning status (ÇAP) document and plan notes need to be obtained from the relevant municipality. The prepared concept project is submitted to the approval of the employer and after the approval is obtained, the preliminary project process begins. The preliminary project is the level before the municipalities issue the license projects for building use. The request for the preliminary project varies according to the municipalities. The diagram in Figure 1 is prepared according to the status of the preliminary project. When starting the preliminary project;

- Firstly, it is necessary to apply for official zoning status. The application is made with the original title deed, ÇAP document and application sketch. There are two different options in the official zoning status application. In the first one, the employer gives a power of attorney to the employer's architect and the architect is authorized to collect all the documents and apply to the relevant institutions. In the second, the employer does all these works himself.
- After the zoning status application is made, the preliminary project application starts to be created. In this process, projects start to be detailed. Detailing is the processing of many details that municipalities find necessary in license projects. For example: drawing the plans exactly, making the precedent tables exactly, placing the elevations and elevations exactly, making the 0.00 elevation, making other calculations, etc. The application for the preliminary project is created together with the site plan of the designed project.
- Prior to the preliminary application, the elevation section (showing where the 0.00 elevation will be taken) and the direction survey (a sketch showing the distances of the parcel and the dimensions of the building to be built, prepared in accordance with the zoning status as a basis for the architectural project) must be taken. After the completion of these documents, the official preliminary application is made.
- During the preliminary application process, projects are examined by rapporteurs. If minor corrections can be made, notes are made on the preliminary project. If there are major changes contrary to the legislation, corrections are required. After the correction of the detected changes, the project approval is obtained. In general, the channel project worked by the mechanical team is submitted to the municipality and after approval, the license projects can be started to be fully created. It should not be forgotten that within the preliminary project processes, mechanical, static and electrical requirements are shared with these disciplines and processed into projects by obtaining information from them.
- After receiving the approval of the preliminary project and channel project, license projects are started to be created. The license project is the projects created for the building to be completely formalized. These projects must be created in accordance with the regulations. In the application for license projects, approved architectural preliminary project, approved channel project, transformer approval, Energy Identity Certificate (EIC), Building Information Form (BIF) document, commitment letter with the project contractor, road participation certificate and excavation certificate are required. In addition to these, drawings of license projects (architectural, static, mechanical, electrical, ground survey) from all disciplines are required. Landscaping and shoring projects vary according to municipalities.

- After the approval of the license projects (architectural, static, mechanical, electrical), these projects are formalized and the final project phase begins. The employer, contractor and architect decide which materials will be used. The reason for this is to avoid problems when proceeding to the application project. Materials are determined as a result of the joint work of the disciplines. After the decisions are made, the application project starts to be drawn. The scope of the application projects may vary according to the contracts made.

BIS covers the process from the permit project application to the completion of the implementation phase of these processes. This process is quite complex and requires many stakeholders to work together. To overcome these complexities of the process with BIM, this study proposes a flexible IDM module that can be used, developed or upgraded.

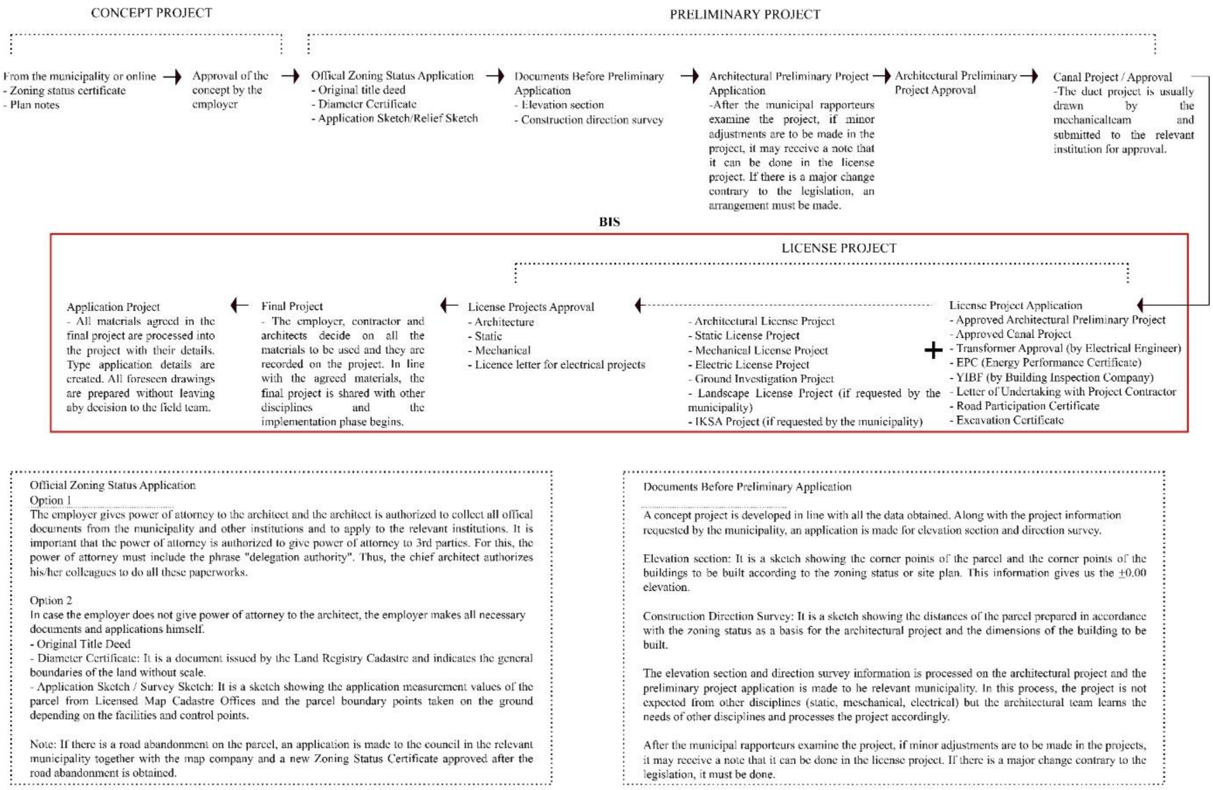

Figure 1: Architectural project phases.

IDM and MVD

Interdisciplinary project design in planning for construction processes needs to be managed using a common data environment that can be used as a communication and communication tool that can be used by every participant in the project as well as increasing transparency in the planning process (Suse et al., 2022).

BuildingSMART has proposed Information Distribution Manuals (IDMs) to manage and assess information sharing between stakeholders within BIM processes. In other words, an IDM (NIBS, 2007; ISO, 2010a) is a modelling language for the flow of information between people and stakeholders. Knowledge sharing in construction processes is process-related because knowledge needs are task or process specific (Venugopal et al., 2015). There is much research in the literature to develop, model and redesign information systems for collaborative processes (Jeon et al., 2021). One explanation for this is that structures and organizations are perceived as unique in each project, which leads to the need to adapt processes and knowledge (Bengt et al., 2011). Being aware of information needs and meeting the information needs of other stakeholders can help in the development of information systems and improve collaboration in general. The IDM can evolve into a legal agreement (NIBS, 2007) to foster digital cooperation between multiple parties.

Around 200 IDMs have been developed by various organizations, including BuildingSMART International (bSI) and the US General Services Administration. However, these IDM documents are not shared as machine-readable data sets that can be easily modified and reused, but as separate files such as Word or PDF documents. This is primarily attributed to the lack of a generally accepted IDM data schema (Jeon et al., 2021). In addition, the literature emphasizes the necessity of IDM and MDV models, but it is not clear with what kind of data they should be built. IDM methods and models can often be tailored to the needs, size, industry and specific requirements of organizations (Lee et al., 2013). Based on this, a new IDM model has been developed taking into account BIS requirements and conditions. Meanwhile, Model View Definition (MVD) is proposed to implement the information exchange requirements of the IDM and to verify whether the derived information conforms to the standard (Xu et al., 2020). This is a pilot study scenario. The accuracy of the model is out of scope. The model can be improved and adjusted for future studies.

Figure 2 briefly illustrates the IDM and MVD processes. Accordingly, the elements represented by times and identified by letters define programs, while the elements represented by circles and numbers symbolize MVDs. This whole process defines the IDM. To summarize these concepts, in an architectural project, MVDs define the file content while IDM defines the overall process.

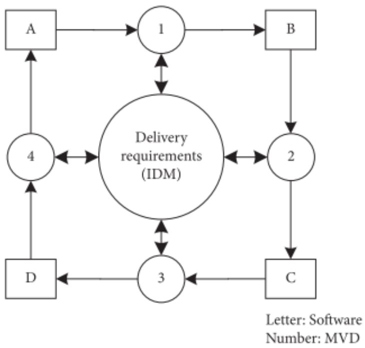

Figure 2: IDM and MVD process.

Findings

As can be seen in Figure 3, an IDM model has been developed for integrating the currently used BIS systems into BIM-based processes. Accordingly, the process starts with an employer. In the architectural project process, first the concept project is completed and then the preliminary project is started. the use of BIM based programs in this process allows the project process to be easily audited, evaluated and flexible design continuously. the architectural project is stored in the BIM cloud as exchange data in a format that can be read and updated by BIM based programs. The civil engineer then evaluates this file and the static projects are completed. The completed file is stored in a single file with the architectural file in a file format that can be read and evaluated by other stakeholders. Then the electrical and mechanical engineer on the same file format prepares electrical and mechanical projects. The exchange data seen here are files with special BIM-based extensions that allow stakeholders' work to be seen and evaluated by other stakeholders, while preventing projects from being changed. In this way, projects can be prepared on a single file without the need for file sharing. Since there is no file sharing, updates, conflicts and stakeholder work on the project can be tracked on a single file and a much more accurate project design process is completed compared to traditional methods. After the architectural project process is completed, the application phase is started. When the process is carried out by using BIM-based programs in the application phase, a suitable application phase is completed without going beyond the prepared project.

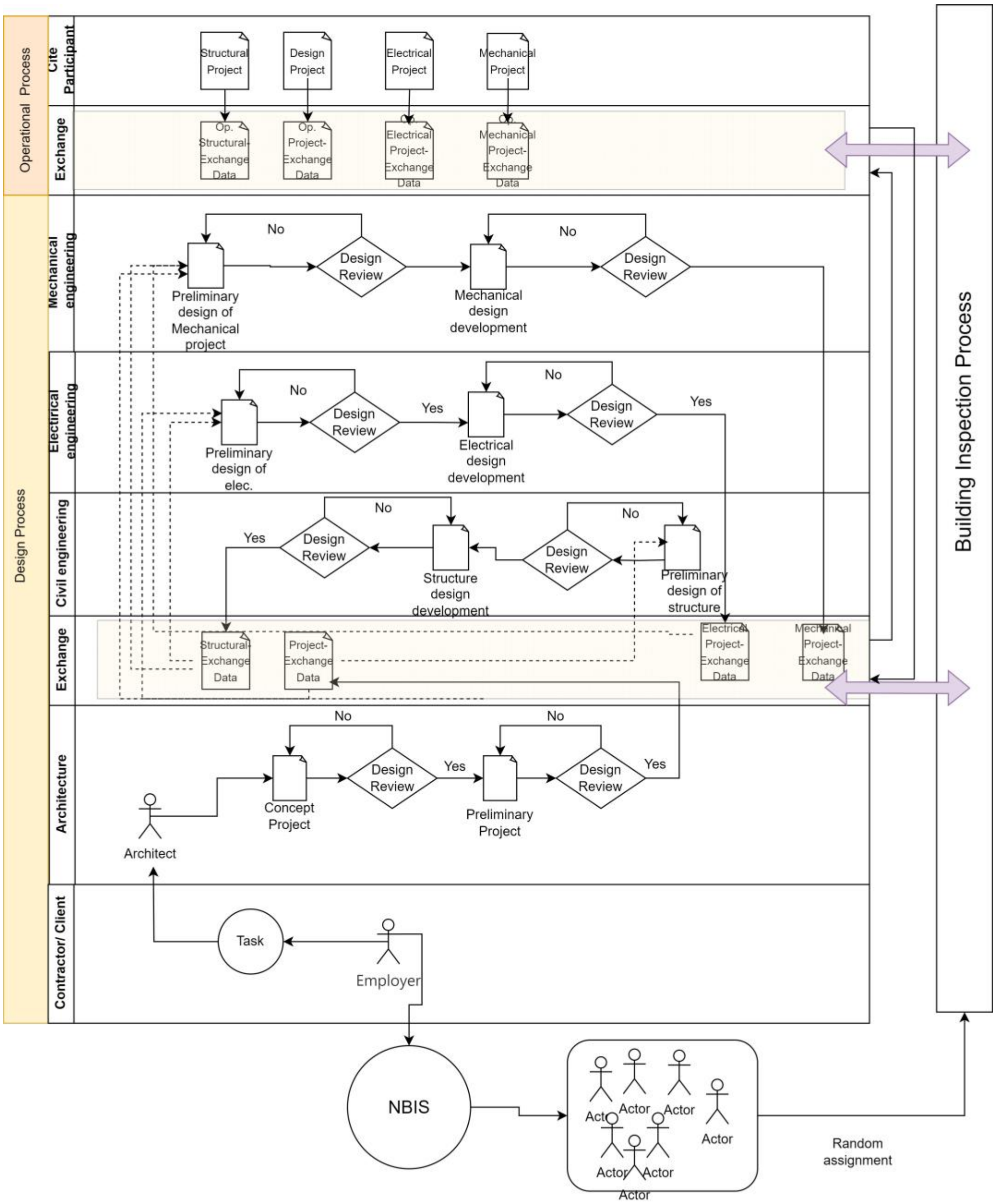

Figure 3: Model proposal for the integration of BIS into BIM processes.

The building supervision system, on the other hand, is actively involved in both project design and implementation. In the IDM model proposal, the digital application of the employer or architect to the National Building Inspection System (NBIS) is the same as the current situation. Assignments are made from random building inspection companies from the NBIS system. The stakeholder assigned in the model is designed in such a way that they can access, access, and monitor the change files, but cannot change them. In this way, it can evaluate whether the works carried out both in the project design and implementation phase are in accordance with the project through a single file. In this way, all project and application processes can be followed digitally through a single file, data loss can be prevented and errors caused by people can be detected in advance. Because all stakeholders work on a single file, no changes will be needed during the implementation phase.

Conclusion

Within the scope of this study, an IDM model is proposed for the integration of the BIS system, which is actively involved in the Turkish construction industry, with BIM-based programs. The proposed model allows all stakeholders to work on a single platform and covers both design and implementation processes. This model minimizes errors caused by people. One of the main reasons for this is that since all stakeholders work from a single file during the project design phase, they can foresee conflicts and incompatibilities that may occur in architectural, static, mechanical and electrical projects. In addition, although the stakeholders work in a single file, thanks to the exchange file format, no stakeholder can interfere with the work of another stakeholder.

The prepared model has a workflow process compatible with the currently used building inspection system. A workflow model that users can easily adapt to has been prepared. This prepared IDM model is open to development and serves as a basis. And it is unique because there has been no previous work on BIM integration of building inspection systems. The prepared IDM model may vary from company to company.

References

Bengt, O., Berard, O., Student, I., Karlshoej, J., & Professor, A. (2011). General rights information delivery manuals to integrate building product information into design. *Proceedings of the CIB W78-W102*, pp. 26-28.

Boysal, V. B. (2022). *4708 Sayılı Yapı Denetimi Hakkında Kanun kapsamındaki yapı denetim sistemi ve sorunları üzerine bir saha çalışması, Osmaniye ili örneği* [Yüksek lisans tezi]. Osmaniye Korkut Ata Üniversitesi.

Demir, M. Ş. (2017). *Güneydoğu Anadolu Bölgesinde yapı denetimi uygulaması ve yeni bir yapı denetimi modeli önerisi* [Yüksek lisans tezi]. Adıyaman Üniversitesi.

Doğan, A. (2013). *Ankara'da yapı denetim sorunlarının belirlenmesiyle ilgili bir saha çalışması* [Yüksek lisans tezi]. Gazi Üniversitesi.

Engin, V. (2022). *Türkiye'de uygulanan yapı denetim sisteminin sorunları ile ilgili yaklaşımlar* [Yüksek lisans tezi]. İstanbul Okan Üniversitesi.

Erdal, D. (2022). *Yapı denetim firmalarının iş sağlığı ve güvenliği açısından sorumlulukları* [Yüksek lisans tezi]. Hitit Üniversitesi.

Güleş, M. (2019). *4708 sayılı Yapı Denetimi Hakkında Kanun'un uygulanmasında karşılaşılan sorunlar ve çözüm önerileri* [Yüksek lisans tezi]. Karatay Üniversitesi.

Güncü, D. (2020). *Yapı denetim kuruluşlarının sorunları ve yapı denetimi sistemindeki sorunlar-Van örneği* [Yüksek lisans tezi]. Van Yüzüncü Yıl Üniversitesi.

Jeon, K., Lee, G., Kang, S., Roh, H., Jung, J., Lee, K., & Baldwin, M. (2021). A relational framework for smart information delivery manual (IDM) specifications. *Advanced Engineering Informatics, 49*, 101319.

Karahan, A. Y. (2008). *İstanbul'da faaliyet gösteren yapı denetim şirketlerinin uygulamaya yönelik karşılaştıkları sorunlar ve çözüm önerilerine yönelik bir araştırma* [Yüksek lisans tezi]. Yıldız Teknik Üniversitesi.

Karaoğlu, E. (2011). *4708 Sayılı Yapı Denetim Kanunu'nun denetimdeki verimliliği* [Yüksek lisans tezi]. Yıldız Teknik Üniversitesi.

Kural, R. (2015). *İnşaat sektöründe yapı denetimi ve Afyonkarahisar ilindeki uygulamaların araştırılması* [Yüksek lisans tezi]. Afyon Kocatepe Üniversitesi.

Lee, G., Park, Y. H., & Ham, S. (2013). Extended process to product modeling (xPPM) for integrated and seamless IDM and MVD development. *Advanced Engineering Informatics, 27*(4), 636-651.

Özkan, G. (2005). *Türkiye'de yapı denetim sistemi ile ilgili yaklaşımlar* [Yüksek lisans tezi]. Yıldız Teknik Üniversitesi.

Süße, M., Münnich, M., Lenz, L., & Ihlenfeldt, S. (2022). Data requirements for factory layout planning and simulation – setting up a module-based concept for information delivery manuals. Proceedings of *IEEE 27th International Conference on Emerging Technologies and Factory Automation*, pp. 1-4.

Taşçı, M. (2017). *Yapı denetimi uygulamaları ve kalite sorunları, Konya örneği* [Yüksek lisans tezi]. Selçuk Üniversitesi.

Venugopal, M., Eastman, C. M., & Teizer, J. (2015). An ontology-based analysis of the industry foundation class schema for building information model exchanges. *Advanced Engineering Informatics, 29*(4), 940-957.

Xu, Z., Abualdenien, J., Liu, H., & Kang, R. (2020). An IDM-based approach for information requirement in prefabricated construction. *Advances in Civil Engineering*, 1-21.

BIM Supported Management of MEP Processes and Cost Impacts in Early Design Phase

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Abstract

This study addresses the advantages and challenges of using Building Information Modeling (BIM) for effective completion of Mechanical, Electrical, and Plumbing (MEP) processes in the Early Design Phase of construction projects. The main focus is how MEP processes can be better integrated using BIM in the early design phase and its contribution in terms of cost, quality, and time. The study involves a literature review on contracts, regulations, and workflows, and includes studies on cases in the industry based on interviews. Based on this, the operation of MEP processes in the early design phase was determined, and the workflow diagram was redesigned. As a result, the study presents the reasons for losses in design, construction, and operational costs, time, and quality due to inadequate planning of MEP processes in the early design phase of BIM-enabled projects, supported by case studies. Recommendations are made based on the redesigned workflow diagram to address these issues.

Keywords: *BIM, early design phase, MEP.*

Introduction

In today's construction industry, Building Information Modeling (BIM) technology has revolutionized the field, especially in Mechanical, Electrical, and Plumbing (MEP) engineering areas. This technology plays a significant role in structural and MEP engineering. MEP coordination is an interdisciplinary practice that requires collaboration among the three main areas of construction: architecture, structure, and mechanical systems. These systems are among the most expensive parts of construction costs, with MEP costs constituting 40% to 60% of total building expenses. Therefore, MEP coordination is crucial throughout the project lifecycle to ensure proper integration of different systems (Hood, 2023; Chiu, 2020).

For complex buildings and light manufacturing facilities, coordinating MEP systems is a significant challenge. It involves detailed positioning and configuration of HVAC, electrical, process piping, fire protection, and other systems. Limitations in current projects include restricted building space, increasing complexity of all building systems, and limited engineering budgets and installation schedules for MEP systems. Combined with the increasing pressures for better, faster, and cheaper projects, these constraints highlight the necessity of advanced workflows in MEP coordination (Tatum, 2000; Korman, 2006).

The accelerated completion of recent construction projects presents unique challenges for MEP coordination. Shortened project timelines mean insufficient time for MEP contractors, requiring quick decision-making and adaptability during design and installation stages. Projects often face reduced design budgets, mandating the delivery of high-quality work at lower costs. This situation necessitates MEP contractors to work more efficiently with limited resources while increasing the need for detailed planning and coordination to prevent potential errors and conflicts during design and construction. Particularly for tight and complex MEP systems, accelerated timelines and tight budgets create additional challenges in the integration and alignment of systems, making the successful completion of projects more complex.

In BIM projects, especially in MEP design, significant advantages are offered in the pre-design phase. These include improved conflict detection, better integrated system designs, and detailed visualizations. However, BIM applications often stop or continue in a limited manner before the construction phase. This results from a lack of integration between design and construction processes. Deviations between structures and MEP layouts can occur during the transition from design to actual construction. These deviations may arise from unexpected site conditions, material changes, or other construction challenges. If the BIM model is not updated and integrated with real-time site information during the construction phase, discrepancies can occur between the designed MEP layout and the actual built structure, leading to issues that may require on-site adjustments or redesign of MEP systems (Wang, 2016).

This study critically examines the role of contracts, regulations, and workflows in MEP processes during the pre-design phase of projects using BIM, highlighting the advantages and disadvantages of completing MEP processes at this stage.

Previous Studies on MEP Processes and Cost Impacts in Early Design Phase: A Comprehensive Review

This study critically examines the role of contracts, regulations, and workflows in Mechanical, Electrical, and Plumbing (MEP) processes during the pre-design phase of projects using Building Information Modeling (BIM). Construction industry professionals have indicated that MEP coordination is one of the most challenging tasks encountered in the delivery process of construction projects (Korman, 2008). The construction and maintenance costs of MEP systems constitute a significant portion of total costs, making the effective tracking and management of spatial changes of great importance (Han, 2012).

The coordination of MEP systems is a fundamental challenge for complex buildings due to the requirements of project participants in design coordination and the extensive exchange of information (Tatum, 2000). Moreover, due to participants' limited budgets and schedules and emerging technical issues, this process often slows down the delivery of projects. Defining responsibilities and distributing risks in BIM is a significant challenge. There can be inconsistencies in the assembly sequence given to the contractor, leading to incompatibility with the BIM model, despite the need for MEP and Architectural groups to work in harmony within the BIM environment (Hamdi, 2014).

In the early design phase, it is important to define the file formats to be used by subcontractors. Projects implementing BIM, like the Sprint Center Arena project, have faced implementation challenges due to weak contractual agreements. The contract failed to clearly define the open file format for digital data received by subcontractors, leading to the emergence of numerous proprietary CAD and other file formats used in design and construction (Foster, 2008).

The integration provided by BIM for MEP contractors allows projects to be completed more effectively and efficiently, contributing to better management in terms of cost and time (Langstaff, 2018). Traditionally, in projects conducted with BIM, MEP networks are often represented as layout designs. However, this approach can cause problems in large and complex facilities.

Especially in complex MEP systems, engineering teams are turning to software that facilitates coordination. BIM is a digital design and documentation system used to optimize design and construction processes, enhancing interdisciplinary coordination and efficiency in complex building projects. (Kermanshahi, 2020) The main task of the BIM Manager is to detail the BIM Execution Plan (BEP) and present it for consultation to all team members in the project (Abotaleb, 2020).

The focus of this study is on how BIM affects MEP processes in the pre-design phase and the balance between the advantages and disadvantages of completing MEP processes at this stage. Given the complexity of MEP systems and their critical role in projects, the impact of BIM in managing these processes plays a significant role in the success of construction projects.

For the integrated implementation of the MEP layout from the pre-design to the construction phase, a practical BIM framework has been developed. This framework categorizes MEP design models in BIM projects into 5 detail levels, providing modeling appropriate to the needs of each stage. These levels are 3D MEP Preliminary Design Model, 3D MEP Detailed Design Model, 3D MEP Construction Design Model, 3D MEP Construction Model, and 3D MEP Prefabrication Model. This distinction allows for more effective coordination of MEP systems at each stage (Wang, 2016).

In compressed construction schedules, it may not be possible for all stakeholders to model in sequence. In such cases, MEP subcontractors develop models simultaneously, but communication and coordination challenges arise due to each model being in the development stage. Once all models are complete, inter-model clashes can be checked. However, emerging clashes can render even well-conceived systems faulty. In this case, MEP subcontractors need to come together to clean up all clashes, update their models, and repeat clash analyses (Lee, 2014).

In sequential stepwise coordination, HVAC systems and pipe systems for Water-based HVAC systems are addressed first. After these systems are completed, they are handed over to the relevant MEP subcontractors. The modeling process involves three main elements: Outside to inside, large to small, and hard to soft. In the outside to inside approach, structural systems are finalized after architectural design, followed by MEP designs. In the large to small approach, elements taking up more space are prioritized. In the hard to soft approach, special measures are taken to prevent hard clashes, as resolving them on-site is more challenging (Lee, 2014).

The integration of MEP services within BIM, especially in terms of placing pipes and ducts in limited ceiling spaces, is a technically challenging process. This coordination effort can take up more than half of the project process and requires a high investment in terms of time. Additionally, reprocessing of MEP systems and the risk of cost overruns can lead to higher costs relative to the total building cost (Teo, 2022).

The examination and dissection of workflow diagrams, focusing on the role of each component within the overall process, is crucial for effective project management in BIM-based MEP design. This is particularly evident in BIM projects, where traditional workflow diagrams are often inadequate in the initial design phases. A more holistic approach that integrates architectural, structural, and mechanical aspects is necessary. Such an approach is vital to ensure that the impact of mechanical decisions on architectural components is not overlooked (Partl, 2019).

The Importance of BIM-Based MEP Coordination in the Early Design Stage: A Case Study on a Multi-Functional Office Project in Moscow

The case study examined in the interviews focuses on a multi-functional office project in Moscow, Russia, conducted by a Turkish construction company. The research explores the coordination processes of mechanical and electrical systems implemented in the project. A notable feature of the project is the presence of mechanical floors in both the basement and the rooftop levels, necessitating the organization of electrical and mechanical teams into two separate groups.

Located in the Gagarinsky District near the Moscow River, this office building project in Moscow is strategically positioned close to some of the city's leading research institutions and the company's first office. The project encompasses a total construction area of 262,000 m², with 161,000 m² over 15 above-ground levels, 98,000 m² across 5 underground levels, and 3,000 m² of outdoor terraces.

This new office building will provide employees with a healthy and sustainable environment for both work and leisure. It includes approximately 110,000 m² of office space and a parking area of 47,000 m², accommodating 1,630 parking bays within a multi-level parking system. The building is designed as a single complex comprising three multi-height wings, with the tallest reaching up to 75 meters, linked by a skylighted central hub.

Effective management of the coordination process ensured that the design phases proceeded systematically, and the construction process continued smoothly. The progress of a complex and challenging project was monitored monthly based on the BIM protocol through federation and coordination models. The federation model was published to the employer monthly, while the coordination models were communicated to all stakeholders on a weekly basis both on a floor basis and on a regional basis via the Common Data Environment (CDE), making coordination meetings more efficient. Project follow-up in accordance with international standards was carried out in accordance with BIM standards. In addition, interdisciplinary work schedules were organized to minimize manpower loss and ensure uninterrupted progress of the construction process. Through the BIM methodology of the client, all disciplines actively participated in the publication and coordination process.

The workflow redesigned initiated with parallel coordination techniques in the basement floors while adopting sequential, step-by-step coordination for the rooftop floors. This bifurcated approach facilitated meticulous planning and coordination across various construction phases, ensuring that both MEP teams—operating in distinctly separate spaces—could efficiently align their efforts. By adopting this structured workflow, the project efficiently managed to mitigate potential conflicts and streamline the integration of mechanical and electrical systems, underscoring the effectiveness of combining parallel and sequential coordination strategies in BIM-enabled environments. In discussing our redesigned workflow, we reference Lu's standard BIM workflow purely as a comparative baseline, illustrating how our tailored approach builds upon and diverges from established practices. This model provides a robust framework for other complex projects by demonstrating how strategic planning and phased coordination can significantly enhance overall project execution and outcomes. In the project, parallel coordination techniques were applied in the basement floors, while sequential step-by-step coordination was used in the rooftop floors. Both approaches required extensive planning and coordination encompassing both basement and rooftop levels. Particularly, the coordination between the two different mechanical teams involved determining shaft locations for the integration of upper and lower mechanical systems. This situation led to the project being viewed as an intersection of both parallel and sequential step-by-step coordination.

In the case study of a pharmaceutical building, two distinct MEP design coordination strategies were implemented, showcasing the effectiveness of parallel versus sequential cascading coordination. The project employed two MEP coordinators, each managing different zones of the building with similar complexity and MEP density. Coordinator A employed a parallel coordination strategy, orchestrating MEP designs concurrently across all trades, which resulted in a lengthy and complex coordination process. Conversely, Coordinator B adopted a sequential cascading strategy, managing MEP designs step-by-step, which proved significantly more efficient, reducing coordination time by a factor of three compared to the parallel strategy. This sequential approach minimized initial clash detections by methodically integrating each system's requirements before proceeding to the next, thus streamlining the resolution process during coordination meetings.

One of the key elements in the project is the design of large-scale ventilation ducts, focusing on both facade exits and distribution points from the shaft. In determining the mechanical design, the floor heights and reservation sizes on structural elements played a significant role. Specifically, the location and dimensions of reservations to be made on steel beams were determined in coordination with the manufacturing company before starting production drawings.

After the channel placement among mechanical systems, the positioning of gravity-directed water pipes was considered, defining the boundaries of other systems. Additionally, the placement of systems into suspended ceiling heights and raised floors was a part of the project. In terms of fire extinguishing systems, the placement of fire cabinets and the positioning of sprinkler main lines were especially important in the project. The layout of these systems was a critical component of the project in terms of overall safety and functionality.

The project serves as an excellent example of integrating these two approaches and analyzing the efficiency of coordination processes and the quality of information flow. Parallel coordination involved other stakeholders starting the modeling process simultaneously, while sequential step-by-step coordination started with HVAC systems and progressed step by step. Both approaches had significant impacts on the process and outcomes of the project.

The parallel coordination approach in the project represented a situation where all stakeholders do not model sequentially in a compressed construction schedule, while sequential step-by-step coordination started with prioritizing HVAC and piping systems, later passing these models to other MEP subcontractors. The integration of these two methods played a critical role in reducing design errors at the start of the project and preventing these errors from leading to significant economic losses later. The combination of these approaches helped reduce information distortions and misunderstandings, facilitating more effective coordination and communication throughout the project process.

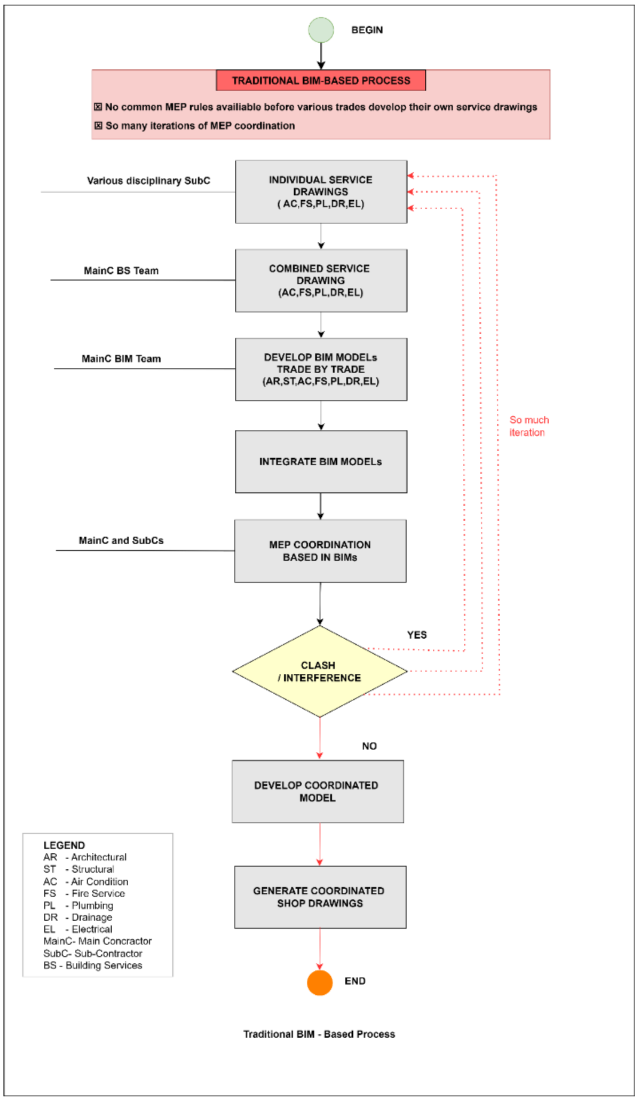

Figure 1: Traditional BIM – based process (Lu, 2018).

This case study highlights the importance of BIM-based MEP coordination in modern and complex building projects and the necessity of developing effective design coordination strategies. How the project combined these approaches and the contributions its results have made to the industry serve as an important example for better understanding, measuring, and predicting the performance of MEP coordination.

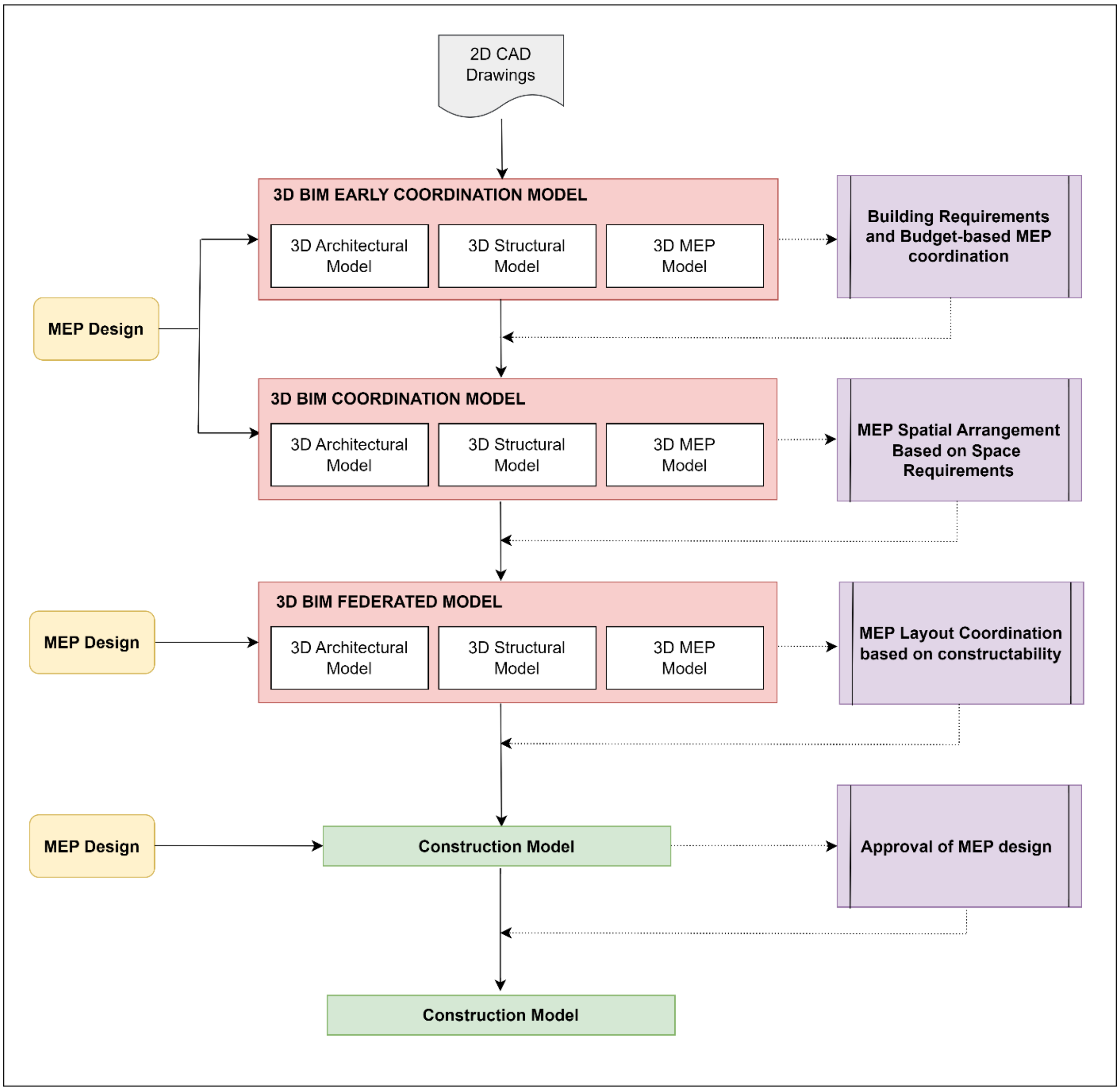

Figure 2: BIM based MEP layout design (Wang, 2016).

Conclusions

The article emphasizes the importance of BIM-based MEP coordination in modern and complex building projects, highlighting the need for effective design coordination strategies in the early design phase. It showcases a case study of a multifunctional office project in Moscow, demonstrating how the integration of parallel and sequential coordination approaches enhances the efficiency of coordination processes and the quality of information flow. The study underlines the role of BIM in reducing design errors, preventing economic losses, and improving coordination and communication in projects, illustrating the significance and benefits of BIM in MEP coordination of complex construction projects.

References

Abotaleb, M. M. (2020). Integrating building information management (BIM) in civil infrastructure coordination: application at LUSAIL Plaza. *Proceedings of International Conference on Civil Infrastructure and Construction*, Katar.

Chiu, W. Y. (2020). Building information modelling for building services engineering: benefits, barriers and conducive measures. *Engineering Construction and Architectural Management*.

Foster, L. L. (2008). *Legal issues and risks associated with building information modeling technology*. Kansas University.

Hamdi, O. F. (2014). Conflicting side of building information modeling implementation in the construction industry. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*.

Han, S. L.-M. (2012). Identification and quantification of non-value-adding effort from errors and changes in design and construction projects. *Journal of Construction Engineering and Management, 138*(1), 98-109.

Hood, G. (2023). *What is MEP coordination in BIM?* https://www.thecadroom.com/what-is-mep-coordination-in-bim/

Kermanshahi, E. K. (2020). Implementation of building information modeling for construction clash detection process in the design stage: a case study of Malaysian Police Headquarter Building. *IOP Conference Series: Earth and Environmental Science, 476.*

Korman, T. M. (2008). Using building information modeling to improve the mechanical, electrical, and plumbing coordination process for buildings. *Proceedings of AEI 2008: Building Integration Solutions.* American Society of Civil Engineers.

Langstaff, C. J. (2018). *Application of mechanical electrical and plumbing contractor's BIM practices to the Cal Poly San Luis Obispo Construction Management Program* [Master thesis].

Lee, G. K. (2014). Parallel vs. sequential cascading MEP coordination strategies: a pharmaceutical building case study. *Automation in Construction, 43*, 170-179.

Lu, Q. V. (2018). A BIM-based approach to automate the design and coordination process of mechanical, electrical, and plumbing systems. *HKIE Transactions, 25*(4), 273-280.

Partl, R. H. (2019). Process model for BIM-based MEP design. *IOP Conference Series: Earth and Environmental Science, 323.*

Tatum, C. B. (2000). Coordinating building systems: process and knowledge. *Journal of Architectural Engineering*, 116-121.

Teo, Y. H. (2022). Enhancing the MEP coordination process with BIM technology and management strategies. Sensors, *22*, 4936.

Korman T. M. (2006). Prototype tool for mechanical electrical and plumbing coordination. *Journal of Computing in Civil Engineering, 20*(1), 38-48.

Wang, J. W. (2016). Building information modeling-based integration of MEP layout designs and constructability. *Automation in Construction*, *61*, 134-146.

Identifying the Obstacles and Prioritizing the Significance Levels for the Adoption of BIM in Turkey

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Abstract

It is known that BIM has many advantages in the construction sector, but various problems are encountered in the transition of developing countries to BIM (Building Information Modeling) processes. Considering the positive impacts of BIM in the construction sector in developed countries, there is perceived resistance to the adoption of this method in Turkey, and the reasons for this resistance are being investigated. This study aims to identify the barriers to the widespread adoption of BIM in Turkey and determine their levels of significance. In the study, 112 number of articles have been reviewed by systematic literature review and the obstacles in the process of transition to BIM in the literature have been identified. Then to determine the prioritized importance of these factors by Analytic Hierarchy Process (AHP) method and to provide strategic solutions for a more effective adoption of BIM in the sector. The study is important in terms of determining the obstacles encountered during the transition to the BIM system according to their importance and developing solutions according to the order of importance. It is thought that this study will contribute to the dissemination of effective BIM applications in the construction sector by identifying the obstacles in the process of transition to BIM in Turkey and developing strategies for their solution.

Keywords: *adoption strategies, Analytic Hierarchy Process, barriers of BIM transition, Building Information Modeling (BIM), construction sector, level of significance.*

Introduction

The construction sector is a fundamental factor for a country's economic growth and urban transformation. This sector is constantly transforming and renewing with the impact of technological developments. One of the most important tools of this transformation is the digital design and construction management process called Building Information Modeling (BIM). BIM refers to a comprehensive approach to integrate, share and manage information throughout the project lifecycle. Turkey shows a significant development in the construction sector with dynamics such as rapid economic growth and urban transformation. However, when BIM is evaluated on a global basis in comparison with other developed countries, it can be stated that Turkey is at the beginning stage (Erdik et al., 2020; Tan, 2021). It is thought that there is resistance to the use of BIM in Turkey and as a result of the researches conducted, it is determined that it is not widely adopted by many companies in Turkey (Namlı et al., 2019). This situation indicates that the potential in the sector is not fully utilized and important opportunities are missed in terms of efficiency. Although the barriers to BIM utilization have been tried to be identified in national and international literature studies, no study has been found on the importance of these barriers in Turkey. In this context, it is of great importance to identify the factors that prevent the widespread use of BIM in Turkey and to offer solutions. Within the scope of this study, it is aimed to identify the barriers to the widespread use of BIM in Turkey and to determine the importance of these barriers. According to the literature research, it has been concluded that most organizations in Turkey are not sufficiently informed about the benefits of the BIM system, the system is not used as much as necessary, and it is not widely used due to many variables such as these (Akkaya, 2012; Kıvırcık, 2016; Öktem, 2016; Karataş, 2018; Ademci, 2018; Elmalı, 2018; Inusah, 2018; Sarıçiçek, 2019). Factors affecting adaptation to technological developments in the construction process are influenced by many parameters such as socio-economic characteristics, political support, educational structure, construction culture. These effects vary from country to country. For this reason, investigating the obstacles in the BIM transition process in Turkey makes the study unique.

Methodology

This study specifically focuses on the resistance to the use of BIM in the Turkish construction industry. The research framework is structured in three successive phases: first, the advantages of BIM processes will be presented and the importance of the transition will be demonstrated. Then, a systematic literature review will be conducted to identify potential barriers that will form the basis for the questions in the questionnaire. The third stage involves the AHP method to identify the importance of BIM barriers. This study, prepared with the AHP method, is a pilot study. The questionnaire was conducted for 10 expert academicians who are engaged in BIM applications and research. Survey results were evaluated, and consistency indices were analysed. Out of 10 studies, only 3 studies were found to be consistent. The final importance indices were presented by averaging the consistent data.

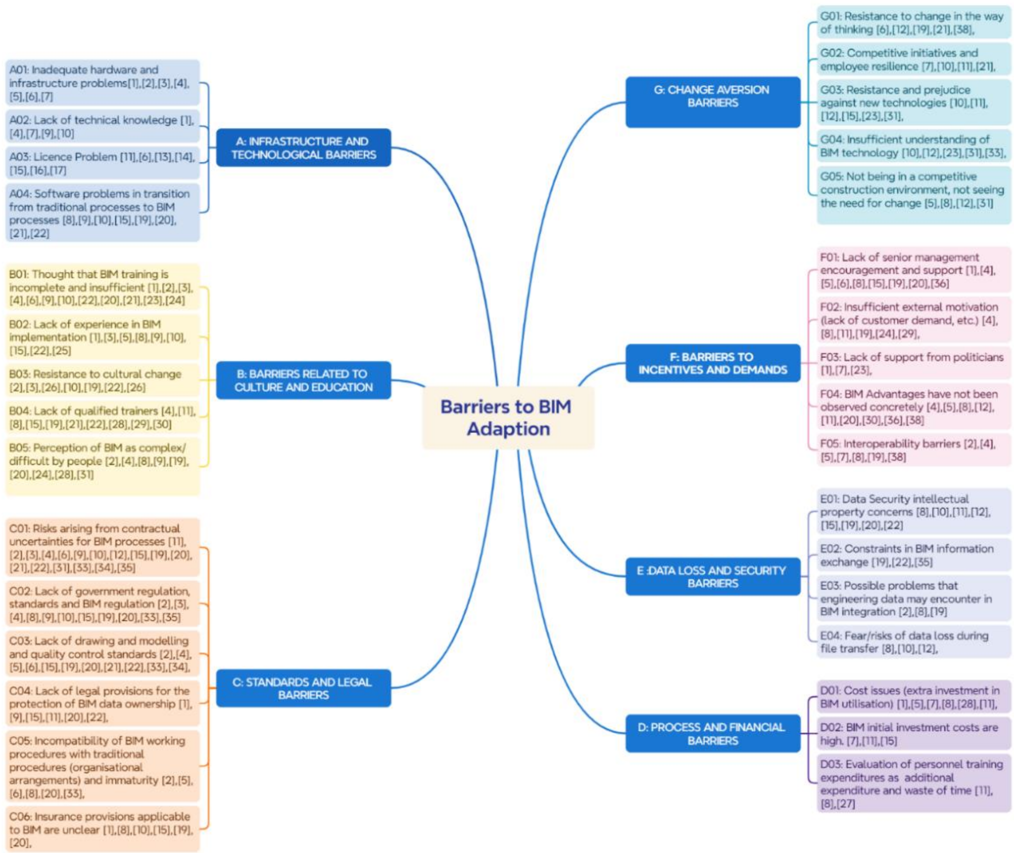
Building Information Modelling

BIM (Building Information Modeling) is a revolutionary process in the construction industry. The positive effects of BIM use in developed countries include improved project completion times, increased cost savings, improved quality control and opportunities for interdisciplinary collaboration. It is a growing approach to integrating different disciplines and a collaborative process of all project parties, optimizing project value by increasing efficiency in all project phases. By involving all project parties and encouraging them to concentrate on the project outcome, it brings all project parties together as a team and prioritizes common goals (Rokooei, 2015). BIM also supports the concept of integrated project delivery, a new project delivery approach to integrate people, systems, business structures and practices into a common process to reduce waste and optimize efficiency in all phases of the project lifecycle (Glick & Guggemos, 2009).

The prevalence of BIM is steadily increasing in various sectors worldwide. Research shows that BIM has become a common language in the construction industry and there is significant growth in its application in infrastructure projects (Andreea, 2022; Giel & Issa, 2013). This is attributed to the numerous benefits that BIM provides, such as improved collaboration, reduced cost and time, enhanced project visualization and better project efficiency. The worldwide BIM industry is expected to grow at a CAGR of 14.9% from 2018 to 2023, driven by government mandates on project efficiency and cost reduction (Andreea, 2022). Considering that the Turkey construction industry continues to develop rapidly technologically in line with these developments in the world, it can be predicted that the importance of BIM will continue to increase and will continue to play an important role in the future of the construction industry in Turkey. Considering all these, BIM emerges as a necessity in the Turkish construction industry (Aladag et al., 2016). However, the general trend of the construction industry in Turkey is that the adoption of BIM will continue to increase.

Systematic Literature Review on the Barriers to BIM Adoption

A Systematic Literature Review (SLR) has been used in the study to determine the obstacles to the adoption of BIM. The SLR technique seeks to locate pertinent studies, assess them critically, and gather and process data from these studies (Liberati et al., 2009). According to this methodology, an SLR was used in this study to methodically gather information on the obstacles to the implementation of BIM in the Turkish construction sector from an open and critical standpoint (Macpherson & Jones, 2010). The SLR method utilized the Web of Science (WoS) database as the database. The protocol used to search (Yu et al., 2022) is summarized as follows: (ALL AREAS) "BIM Implementation" OR "Building Information Modeling Implementation" AND "Barriers" OR "challenges" OR "obstacles" AND “Success Factor” NOT “infrastructure”. The initial results of the search, which had a span of 2000 to 2023, included 2796 publications. Subsequently, precise inclusion and exclusion standards have implemented throughout the screening stage. In this particular context, the 2684 questionnaire and all obtained documents were examined. In the conclusion, 112 articles have been selected to act as the foundation for the survey questions. As a result of the systematic literature review, 32 barriers were identified and grouped under sub-headings. Sub-headings were then organized under 7 main headings (Figure1).



[1](Van et al., n.d.), [2](Ma et al., 2022), [3](Olanrewaju et al.), [4](Saka & Chan, 2019), [5](Olanrewaju et al., 2022), [6](Gharaibeh et al., 2022), [7](Hyarat et al., 2022), [8](T. Tan et al., n.d.), [9](Kineber et al., 2023), [10](Waqar et al., 2023), [11](Erdik et al., 2020), [12] (Durdyev et al., 2022), [13](Alwisy et al., 2019), [14](Calitz & Wium, 2022), [15](Tabatabaee et al., 2021), [16](Charlson & Dimka, 2021), [17](Bosch-Sijtsema et al., 2017), [18](Jin et al., 2019), [19](Zhou et al., 2019), [20](Charef et al., 2019), [21](S. Tan & Gumusburun Ayalp, 2022)], [22] (Wu et al., 2021), [23] (Piroozfar et al., 2019), [24] (Kim et al., 2020), [25] (Akal et al., 2022),[26] (Khurshid et al., 2023), [27](Tan, 2021), [28](Hussain et al., 2022), [29](Rokooei, 2015), [30](Nguyen & Nguyen, 2021), [31](Stanley & Thurnell, 2014),[32](Chen et al., 2023), [33](Mahmoud et al., 2022),[34](Azhar et al., 2012), [35](Nasila & Cloete, 2018), [36](Wu & Jin, 2021), [37](Aladag et al., 2016), [38] (Munianday et al., 2023),

Figure 1: Barriers to BIM adoption.

Analyzing the Data

AHP is a mathematically based method that responds to the selection problem for more than two options among multi-criteria decision-making methods. This method, developed by Thomas L. Saaty to solve multi-criteria problems, is applied by ranking the criteria and sub-criteria that the decision maker has determined for the options according to their own order of importance, and then ranking the available options according to Saaty's 1-9 scale (Figure 2) and prioritizing them in the order of criteria. AHP, which is a widely used method in multiple decision making, is a measurement method applied with the help of measurable criteria and mathematical operations. Knowledge and experience are as important as data for the decision maker to select the criteria well and to create a hierarchy in line with those criteria. The success of this method comes from its ability to be applied in simple and different conditions (Tombuş & Ozulu, 2007; Demiroğlu, 2020).

Scale	Description
1	The two driving factors have the same importance
3	One driving factor is slightly more important than the other one
5	One driving factor is obviously more important than the other one
7	One driving factor is strongly more important than the other one
9	One driving factor is extremely more important than the other one
2, 4, 6, 8	The importance between each of the above two scales

Note: The comparison between driving factor *i* and *j* is a_{ij}, then comparison between driving factor *j* and *i* is a_{ji}.

Figure 2: Assessment scales of each driving factor.

When using this analysis method, pairwise comparisons are made on a matrix. Since the diagonal values for the comparison matrix created will give the comparison of the criteria with itself, they have equal importance, i.e., the numerical value should be 1. Since the result of the pairwise comparison and the criteria compared pairwise and the values given to them from 1 to 9 are under the control of the decision maker, the result in the factors should be consistent. In order to measure whether this consistency exists, a validation method is proposed. Consistency ratio (CR) is used to test the consistency of the factors (Figure 3).

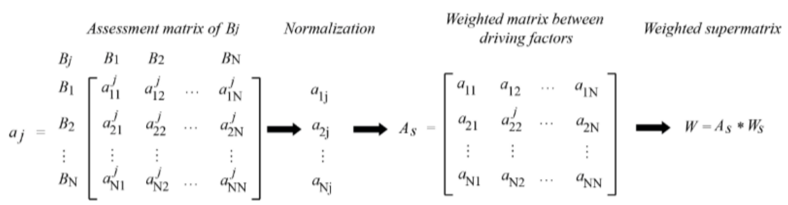


Figure 3: Overview of the weighted supermatrix.

Findings

The results of the AHP analysis are shown in Table 1 in the study, the internal consistency of the AHP analysis results was evaluated. Each main heading was evaluated within itself. Accordingly, the consistency index for "A: Infrastructure And Technological Barriers" was CR: 0.068, "B: Barriers Related To Culture And Education" parameter CR: 0.083, "C: Standards And Legal Barriers" parameter CR: 0.078, "D: Process And Financial Barriers" parameter CR: 0.012, "E : Data Loss And Security Barriers" parameter CR: 0.028", F: Barriers To Incentives And Demands" parameter CR: 0.095, "G: G: Barriers To Change Reluctance" parameter CR: 0.091. According to the AHP analysis, a CR value less than 0.1 indicates that the survey result is consistent.

Table 1. Identification and ranking of severity for BIM barriers.

Headings	Barriers to BIM Adoption	Eigenvector	Severity (%)	Rank	CR
A: Infrastructure And Technological Barriers	A01: Inadequate hardware and infrastructure problems	0.337	8.32	**3**	0.068
	A02: Lack of technical knowledge	2.578	59.27	**1**	
	A03: License Issue	0.178	4.40	**4**	
	A04: Software issues in the transition from traditional processes to BIM processes	1.202	28.02	**2**	
B: Barriers Related To Culture And Education	B01: The idea that BIM training is incomplete and insufficient	1.307	23.43	**2**	0.083
	B02: Lack of experience in BIM implementation	0.686	13.18	**3**	
	B03: Resistance to cultural change	3.136	53.33	**1**	
	B04: Lack of qualified trainers	0.335	6.65	**4**	
	B05: BIM is perceived as complex/ difficult by people	0.175	3.39	**5**	
C: Standards And Legal Barriers	C01: Risks arising from contractual uncertainties for BIM processes	0.280	4.60	**5**	0.078
	C02: Lack of government regulation, standards and BIM regulation	2.958	42.58	**1**	
	C03: Lack of drawing and modeling and quality control standards	0.540	8.68	**4**	
	C04: Lack of legal provisions for the protection of BIM data ownership	0.991	15.00	**3**	
	C05: Incompatibility of BIM working procedures with traditional procedures (organizational arrangements) and immaturity	1.842	26.58	**2**	
	C06: Insurance provisions applicable to BIM are unclear	0.156	2.52	**6**	
D: Process And Financial	D01: Cost issues (extra investment in using BIM)	1.469	48.66	**1**	0.012
	D02: High initial investment costs for BIM.	1.313	43.53	**2**	

	D03: Evaluating staff training expenditures as additional expenditure and waste of time	0.235	7.82	**3**	
E : Data Loss And Security Barriers	E01: Data Security intellectual property concerns	0.205	5.07	**4**	0.028
	E02: Constraints in BIM information exchange	1.053	25.56	**2**	
	E03: Potential problems that engineering data may encounter in BIM integration	2.386	57.64	**1**	
	E04: Fear/risks of data loss during file transfer	0.407	11.72	**3**	
F: Barriers To Incentives And Demands	F01: Lack of top management encouragement and support	1.807	30.77	**2**	0.095
	F02: Insufficient external motivation (lack of customer demand, etc.)	0.306	5.98	**4**	
	F03: Lack of support from politicians	0.687	12.97	**3**	
	F04: BIM Advantages have not been observed concretely	2.737	47.21	**1**	
	F05: Interoperability barriers	0.156	3.04	**5**	
G: Barriers To Change Reluctance	G01: Resistance to changing ways of thinking	1.415	25.34	**2**	0.091
	G02: Competitive initiatives and employee resistance	0.645	12.23	**3**	
	G03: Resistance and prejudice against new technologies	3.215	53.51	**1**	
	G04: Insufficient understanding of BIM technology	0.163	3.19	**5**	
	G05: Not being in a competitive construction environment, not seeing the need for change	0.289	5.70	**4**	

- According to the AHP analysis results, the most important factor under the heading "A: A: Infrastructure and Technological Barriers" is "A02: Lack of technical knowledge".
- The most important factor under the heading "B: Barriers Related to Culture and Education", the most important factor is "B03: Resistance to cultural change".
- The most important factor under the heading "C: Standards and Legal Barriers ", the most important factor is "C02: Lack of government regulation, standards and BIM regulation".
- The most important factor under the heading "D: Process and Financial Barriers", the most important factor is "D01: Cost issues (extra investment in using BIM)".
- The most important factor under the heading "E: Data Loss And Security Barriers", the most important factor is" E03: Potential problems that engineering data may encounter in BIM integration ".
- The most important factor under the heading "F: Barriers to Incentives and Demands", the most important factor is "F04: BIM Advantages have not been observed concretely".
- The most important factor under the heading "G: Barriers to Change Reluctance", the most important factor is "G03: Resistance and prejudice against new technologies".

Conclusion

This research aimed to identify and evaluate the factors that accelerate the transition to BIM in the Turkish construction industry. Through a systematic literature review, the factors affecting the BIM transition processes were identified. In the study, obstacles in the transition to BIM processes using SLR were identified. Then, the importance levels of these obstacles detected using the AHP method were determined. The results show that the obstacles to the transition to BIM processes in the Turkish construction industry are quite different and complex and include various factors such as "lack of technical knowledge, related to culture and education, standards and legal, process and financial barriers, data loss and security, ıncentives and demands, and reluctance, etc." when the factors under these headings are examined, important difficulties can be seen as "lack of technical knowledge, resistance to cultural change, lack of government regulation, standards and BIM regulation, cost issues (extra investment in using BIM)", potential problems that engineering data may it has been determined that "encounter in BIM integration, BIM advantages have not been observed concretely, resistance and prejudice against new technologies".

When the construction systems of developed countries are examined, it is seen that BIM processes are actively used. Within the scope of the study, the advantages of BIM in the project and construction stages are also revealed. It is obvious that the transition to BIM processes will have many advantages for the construction industry in Turkey, which is one of the developing countries. It is necessary to develop solution suggestions according to the severity of the obstacles that may occur in BIM processes. Effectively addressing these critical obstacles is important in removing obstacles to BIM transition processes in the construction industry. Factors affecting adaptation to technological developments in the construction process are influenced by many parameters such as socio-economic characteristics, political support, educational structure, construction culture. These effects vary from country to country. For this reason, investigating the obstacles in the BIM transition process in Turkey makes the study unique.

In conclusion, the information obtained from this study provides valuable perspectives on formulating the barriers to transitioning BIM processes in the Turkish construction industry. By overcoming these obstacles, the industry can move towards a more efficient construction management process.

References

Ademci, M. E. (2018). *An analysis of BIM adoption in Turkish architectural, engineering and construction (AEC) industry.* [Master thesis]. Mimar Sinan Fine Arts University.

Akal, A. Y., Kineber, A. F., & Mohandes, S. R. (2022). A phase-based roadmap for proliferating BIM within the construction sector using DEMATEL technique: perspectives from Egyptian practitioners. *Buildings*, *12*(11), 1805.

Akkaya, D. (2012). *İnşaat sektöründe yapı bilgi modellemesi hakkında inceleme* [Master thesis]. Yıldız Technical University.

Aladag, H., Demirdögen, G., & Isık, Z. (2016). Building information modeling (BIM) use in Turkish construction industry. *Procedia Engineering*, *161*, 174-179.

Alkan, R. M., Murat Ozulu, I., İlçi, V., Engin Tombuş, F., & Şahin, M. (2017). Usability of GNSS technique for cadastral surveying. *Cadastre: Geo-Information Innovations in Land Administration*, 77-91.

Alwisy, A., Bu Hamdan, S., Barkokebas, B., Bouferguene, A., & Al-Hussein, M. (2019). A BIM-based automation of design and drafting for manufacturing of wood panels for modular residential buildings. *International Journal of Construction Management*, *19*(3), 187-205.

Andreea, G. (2022). Building information modelling (BIM) and engineering evolution in a digital world. *Proceedings of International Scientific Conference ERAZ: Knowledge Based Sustainable Development*, pp. 153-161.

Azhar, S., Khalfan, M., & Maqsood, T. (2012). Building information modeling (BIM): now and beyond. *Australasian Journal of Construction Economics and Building*, *12*(4), 15-28.

Ben Mahmoud, B., Lehoux, N., Blanchet, P., & Cloutier, C. (2022). Barriers, strategies, and best practices for BIM adoption in Quebec prefabrication small and medium-sized enterprises (SMEs). *Buildings*, *12*(4), 390.

Bosch-Sijtsema, P., Isaksson, A., Lennartsson, M., & Linderoth, H. C. (2017). Barriers and facilitators for BIM use among Swedish medium-sized contractors-"We wait until someone tells us to use it". *Visualization in Engineering*, *5*, 1-12.

Calitz, S., & Wium, J. A. (2022). A proposal to facilitate BIM implementation across the South African construction industry. *Journal of the South African Institution of Civil Engineering, 64*(4), 29-37.

Charef, R., Emmitt, S., Alaka, H., & Fouchal, F. (2019). Building information modelling adoption in the European Union: an overview. *Journal of Building Engineering*, *25*, 100777.

Charlson, J., & Dimka, N. (2021). Design, manufacture and construct procurement model for volumetric offsite manufacturing in the UK housing sector. *Construction innovation*, *21*(4), 800-817.

Chen, Y., Cai, X., Li, J., Lin, P., Song, H., Liu, G., & Ma, X. (2023). The values and barriers of BIM implementation combination evaluation based on stakeholder theory: a study in China. *Engineering, Construction and Architectural Management*, *30*(7), 2814-2836.

Demiroğlu, B. (2020). *Ankara polatlı bölgesindeki kırsal yerleşim yerlerinin oluşum ve gelişim analizi* [PhD thesis]. Konya Technical University.

Durdyev, S., Ashour, M., Connelly, S., & Mahdiyar, A. (2022). Barriers to the implementation of Building Information Modelling (BIM) for facility management. *Journal of Building Engineering*, *46*, 103736.

Elmalı, Ö. (2018). *Türkiye'de yapı bilgi modellemesi (BIM) farkındalığının ve hukuki zorunluluğunun araştırılması* [Master thesis]. Erciyes University.

Erdik, M., & Tülübaş Gökuç, Y. (2020). Türk yapı sektöründe yapı bilgi modellemesinin adaptasyonu. *Balıkesir Üniversitesi Fen Bilimleri Enstitüsü Dergisi*, *22*(1), 159-171.

Giel, B., & Issa, R. R. (2013). Quality and maturity of BIM implementation in the AECO industry. *Applied Mechanics and Materials*, *438*, 1621-1627.

Gharaibeh, L., Matarneh, S. T., Eriksson, K., & Lantz, B. (2022). An empirical analysis of barriers to building information modelling (BIM) implementation in wood construction projects: evidence from the Swedish context. *Buildings, 12*(8), 1067.

Glick, S., & Guggemos, A. (2009). IPD and BIM: benefits and opportunities for regulatory agencies. *Proceedings of 45th Associated Schools of Construction National Conference*.

Hussain, M., Memon, A. H., & Bachayo, A. (2022). Building information modeling in construction industry of Pakistan: merits, demerits and barriers. *Journal of Applied Engineering Sciences*, *12*(1), 43-46.

Hyarat, E., Hyarat, T., & Al Kuisi, M. (2022). Barriers to the implementation of building information modeling among Jordanian AEC companies. *Buildings*, *12*(2), 150.

Inusah, Y. (2018). *Türk inşaat sektöründe yapı bilgi modellemesi (YBM) uygulamalarının yaygınlığı ve uygulamalardaki başarı düzeyleri üzerine bir inceleme* [Master thesis]. Akdeniz University.

Jin, Z., Gambatese, J., Liu, D., & Dharmapalan, V. (2019). Using 4D BIM to assess construction risks during the design phase. *Engineering, Construction and Architectural Management*, *26*(11), 2637-2654.

Karataş, İ. (2018). *Danışmanlık hizmetlerinde yapı bilgi modelleme (Building Information Modeling-BIM) sisteminin uygulanabilirliğinin incelenmesi* [Master thesis]. Osmaniye Korkut Ata University.

Khurshid, K., Danish, A., Salim, M. U., Bayram, M., Ozbakkaloglu, T., & Mosaberpanah, M. A. (2023). An in-depth survey demystifying the Internet of Things (IoT) in the construction industry: unfolding new dimensions. *Sustainability*, *15*(2), 1275.

Kıvırcık, İ. (2016). *An investigation into the building information modeling applications in the construction project management* [Master thesis]. Istanbul Technical University.

Kim, K. P., Freda, R., & Nguyen, T. H. D. (2020). Building information modelling feasibility study for building surveying. *Sustainability*, *12*(11), 4791.

Kineber, A. F., Massoud, M. M., Hamed, M. M., Alhammadi, Y., & Al-Mhdawi, M. K. S. (2023). Impact of overcoming BIM implementation barriers on sustainable building project success: a PLS-SEM approach. *Buildings*, *13*(1), 178.

Kocakaya, M. N., Namlı, E., & Işıkdağ, Ü. (2019). Building information management (BIM), a new approach to project management. *Journal of Sustainable Construction Materials and Technologies*, *4*(1), 323-332.

Liberati, A., Altman, D. G., Tetzlaff, J., Mulrow, C., Gøtzsche, P. C., Ioannidis, J. P., & Moher, D. (2009). The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration. *Annals of Internal Medicine*, *151*(4), W-65.

Ma, X., Darko, A., Chan, A. P., Wang, R., & Zhang, B. (2022). An empirical analysis of barriers to building information modelling (BIM) implementation in construction projects: evidence from the Chinese context. *International Journal of Construction Management*, *22*(16), 3119-3127.

Macpherson, A., & Jones, O. (2010). Strategies for the development of International Journal of Management Reviews. *International Journal of Management Reviews*, *12*(2), 107-113.

Munianday, P., A. Rahman, R., & Esa, M. (2023). Case study on barriers to building information modelling implementation in Malaysia. *Journal of Facilities Management*, *21*(4), 511-534.

Nasila, M., & Cloete, C. (2018). Adoption of Building Information Modelling in the construction industry in Kenya. *Acta Structilia*, *25*(2), 1-38.

Nguyen, D. P. (2021). Barriers in BIM adoption and the legal considerations in Vietnam. *International Journal of Sustainable Construction Engineering and Technology*, *12*(1), 283-295.

Olanrewaju, O. I., Chileshe, N., Babarinde, S. A., & Sandanayake, M. (2020). Investigating the barriers to building information modeling (BIM) implementation within the Nigerian construction industry. *Engineering, Construction and Architectural Management*, *27*(10), 2931-2958.

Olanrewaju, O. I., Kineber, A. F., Chileshe, N., & Edwards, D. J. (2022). Modelling the relationship between Building Information Modelling (BIM) implementation barriers, usage and awareness on building project lifecycle. *Building and Environment*, *207*, 108556.

Öktem, S. (2016). *BIM'e geçiş sürecinin organizasyonel ve operasyonel çerçevesi* [Master thesis]. İstanbul Technical University.

Piroozfar, P., Farr, E. R., Zadeh, A. H., Inacio, S. T., Kilgallon, S., & Jin, R. (2019). Facilitating building information modelling (BIM) using integrated project delivery (IPD): a UK perspective. *Journal of Building Engineering*, *26*, 100907.

Rokooei, S. (2015). Building information modeling in project management: necessities, challenges and outcomes. *Procedia-Social and Behavioral Sciences*, *210*, 87-95.

Saka, A. B., & Chan, D. W. (2020). Profound barriers to building information modelling (BIM) adoption in construction small and medium-sized enterprises (SMEs): an interpretive structural modelling approach. *Construction Innovation*, *20*(2), 261-284.

Sarıçiçek, T. (2019). *Türkiye'de mimarlık şirketleri için BIM uygulama yol haritası* [Master thesis]. Hasan Kalyoncu University.

Stanley, R., & Thurnell, D. (2014). The benefits of, and barriers to, implementation of 5D BIM for quantity surveying in New Zealand. *Australasian Journal of Construction Economics and Building*, *14*(1), 105-117.

Tan, S., & Gumusburun Ayalp, G. (2022). Root factors limiting BIM implementation in developing countries: sampling the Turkish AEC industry. *Open House International, 47*(4), 732-762.

Tabatabaee, S., Mahdiyar, A., & Ismail, S. (2021). Towards the success of Building Information Modelling implementation: a fuzzy-based MCDM risk assessment tool. *Journal of Building Engineering*, *43*, 103117.

Tan, S. (2021). *Türk inşaat sektöründe bim uygulamalarının yaygın kullanılmamasına meden olan faktörlerin belirlenmesi* [Master thesis]. Hasan Kalyoncu University.

Tan, T., Chen, K., Xue, F., & Lu, W. (2019). Barriers to building information modeling (BIM) implementation in China's prefabricated construction: an interpretive structural modeling (ISM) approach. *Journal of Cleaner Production*, *219*, 949-959.

Tombuş, F. E. (2005). *Uzaktan algılama ve coğrafi bilgi sistemleri kullanılarak erozyon risk belirlemesine yeni bir yaklaşım, Çorum ili örneği* [Master thesis]. Anadolu University.

Van Roy, A. F., & Firdaus, A. (2020). Building information modelling in Indonesia: Knowledge, implementation and barriers. *Journal of Construction in Developing Countries*, *25*(2), 199-217.

Waqar, A., Qureshi, A. H., & Alaloul, W. S. (2023). Barriers to building information modeling (BIM) deployment in small construction projects: Malaysian construction industry. *Sustainability*, *15*(3), 2477.

Wu, P., Jin, R., Xu, Y., Lin, F., Dong, Y., & Pan, Z. (2021). The analysis of barriers to BIM implementation for industrialized building construction: a China study. *Journal of Civil Engineering and Management*, *27*(1), 1-13.

Wu, Z., Lu, Y., He, Q., Hong, Q., Chen, C., & Antwi-Afari, M. F. (2022). Investigating the key hindering factors and mechanism of BIM applications based on social network analysis. *Buildings*, *12*(8), 1270.

Yu, R., Ostwald, M. J., Gu, N., Skates, H., & Feast, S. (2022). Evaluating the effectiveness of online teaching in architecture courses. *Architectural Science Review*, *65*(2), 89-100.

Zhou, Y., Yang, Y., & Yang, J. B. (2019). Barriers to BIM implementation strategies in China. *Engineering, Construction and Architectural Management*, *26*(3), 554-574.

Use of Building Information Modeling (BIM) in the Design Phase in Rail System Applications in Turkey

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Abstract

Thanks to information and information technology developments on a global scale, innovative advances are seen in the construction sector. Considering the locomotive effect of the construction sector in the Turkish economy; It has emerged that there is a need to carry out change studies in parallel with the development of technology in the sector. In the Turkish Construction Industry, especially in large-scale investments such as public projects, the common goal of project management processes is to increase efficiency and quality, which has led to the adoption of the concept of Building Information Modeling (BIM). Istanbul Metropolitan Municipality (IBB) has required the use of BIM in the planning, design, construction, operation and maintenance stages of large metro projects for the last 10 years. The first application in this regard is the Kabataş-Mecidiyeköy-Mahmutbey (KMM) Metro Line Project, the construction of which started in 2013 under the ownership of the Istanbul Metropolitan Municipality European Side Rail Systems Directorate. The innovative project-based movement shed light on the next metro project tender practices. In this study, literature research and design phase evaluation were conducted regarding the effects of BIM application on project management stages. Based on the findings of the design phase of the KMM Metro Line Project, where BIM was first applied, the Mahmutbey-Bahçeşehir-Esenyurt (MBE) Metro Line Project, which is the continuation of this line and is still under construction, was examined. Specifically, for this project, the use of the BIM system in the design phase will be examined and its benefits and problems encountered will be discussed.

Keywords: *building information modeling (BIM), construction projects, rail systems.*

Introduction

Nowadays, it is becoming increasingly important to adapt to constantly changing project environmental conditions and minimize uncertainties in the construction industry. For this purpose, the information technology systems developed offer effective solutions in project production and management processes. In particular, BIM is a promising development in the architecture, engineering and construction industries (AEC). BIM is designed to make project processes more efficient in the construction industry, which is known for its multi-layered structure. This technology increases information sharing, strengthens communication and encourages collaboration among project stakeholders. As a result, Building Information Modeling stands out as a powerful tool to reduce uncertainties and minimize risks in construction projects. (Eastman et al., 2011).

Building Information Modeling in Construction Project Management

"Management of construction projects requires modern management knowledge and understanding of all construction processes. Management systems differ with changes in technology, organizational arrangements or procedures, and changes in new features and methods." (Rokooei, 2015).

"The project life cycle includes design, planning, construction, operation and maintenance phases. Building information modeling is a process and creates a general framework for developing a data-rich model. This model can be used by all project stakeholders in the project life cycle at any time. It acts as a gateway to add, remove, update or change." (Meadati, 2009).

BIM Handbook (2011) defines BIM as a computer-aided modeling technology that focuses on the analysis of production, communication and building information models for the purpose of information management in construction projects (BIM Handbook, 2011). BIM can create a common language between all parties and system sections in a project and turn these participants into an integrated team. (Rokooei, 2015).

"Construction project management is a set of activities to determine how, when, and by whom work will be performed, including all lifecycle activities. BIM capabilities on construction projects align with PMBOK knowledge areas because the nature and role of each element are similar." Therefore, BIM can be considered an effective and powerful tool in project management in the construction industry. (Rokooei, 2015).

PMBOK knowledge area	Definition	Criterion	Positive consideration
Integration Management	Unification, consolidation, articulation, and integrative actions	Coordination	Improvement
Scope Management	Defining and controlling what is and is not included in the project	Scope	Clarification
Time Management	Accomplish timely completion of the project	Time	Reduction or Control
Cost Management	Planning, estimating, budgeting, and controlling costs	Cost	Reduction or Control
Quality Management	Quality planning, quality assurance, and quality control	Quality	Increase or Control
Human resource Management	Organize and manage the project team	Organization	Improvement
Communications Management	Timely and appropriate generation, collection, distribution, storage, retrieval, and disposition of project information	Communication	Improvement
Risk (uncertainty) Management	Increase the probability and impact of positive events, and decrease the probability and impact of adverse events	Risk	Negative risk reduction
Procurement Management	Purchase or acquire the products, services, or results needed from outside the project team to perform the work	Procurement	Help

Figure 1: Success criteria based on PMBOK knowledge areas (Fazli et al., 2014).

"Integration management is the first topic area of the PMBOK, which has the same function as BIM. BIM integrates the information, plans, and efforts of all parties involved in the project. BIM also includes Objects that can be categorized and grouped into different groups, as in the scope of the project, different aspects of a building Another feature of BIM is its cost and duration management capacity, which can be used in 4D and 5D. In this context, it provides parallelism with cost management and duration management within the scope of PMBOK. It shows all risks related to a feasible construction project and construction risks. A powerful tool in mitigating conflict errors in BIM acts as a quality process that visually organizes and analyzes outages.BIM facilitates professionalism among all counterparts, including project procurement, designers and engineers, ensuring effective and direct communication links. It is a fundamental feature.” (Rookoei, 2015).

The usage areas of BIM are examined under 3 main headings: pre-construction, construction and post-construction phases, as described in the BIM Handbook (BIM Handbook, 2011). Since the aim of this study is to examine the use of BIM in the design phase of rail systems, the literature has only focused on the pre-construction design phase.

Pre-production Phase

In the project life cycle, the pre-construction phase is an important phase and greatly affects the success of construction projects. Decisions taken at the pre-construction stage directly affect the performance of the project in the later stages (Kıvırcık, 2015). When used from the beginning stages of the project, BIM contributes greatly to creating an effective road map for the pre-production phase. This increases efficiency, strengthens communication and helps minimize risks throughout the entire life cycle of the project. BIM is an information technology-supported approach to managing design data in the architecture, engineering, construction and facility management sectors. BIM increases interdisciplinary collaboration with actions such as creating compatible data, detecting conflicts and facility management (Ozorhon, 2018). Therefore, using BIM in the pre-construction phase enables project stakeholders to develop a better understanding, reduce design errors and use resources more efficiently.

Design Phase

Eastman et al. (2011) in their opinion; the main advantage of BIM is the concept, feasibility and design analysis in the pre-construction phase, which leads to increased building performance and quality. It is a more accurate design visualization. It is the possibility of automatic and easy correction when changes are necessary. The production of 2D drawings enables early collaboration between multiple project participants. It is the preparation of cost estimates at the design stage. Energy efficiency and sustainability studies are the main advantages in the design phase of a construction project. (Rokooei, 2015). BIM also synchronizes design and construction planning. Detects design errors and deficiencies. It uses design models as the basis for manufacturing components and enables the application of lean construction techniques during the construction phase (Rokooei, 2015).

"The construction industry has used the design phases of structures as milestones to measure the time it takes to complete the overall design of construction projects. It is generally divided into, but not limited to, schematic design, design development, and production of construction documents.". According to Azhar et al. (2011), architects and engineers can take advantage of BIM applications in creating schematic design, application project and system details at different stages of project design.

According to Rüveyda et al. (2022), although many companies claim to use BIM, they do not fully implement the BIM process. It is seen that companies that use only the 3D design phase of BIM do not fully implement the process consisting of a total of 8 dimensions. In this way, it is not possible to obtain sufficient efficiency from BIM, and the targeted cost and time savings are also missing.

Benefits of Using BIM in the Design Phase

With reference to BIM Handbook (2011), the benefits of using building information modeling in the Design Process are as follows (BIM Handbook, 2011):

- Visualizations of the design can be made more accurately and at earlier stages
- Automatic updating of model-related information based on changes made in the design
- Producing accurate and compatible 2D drawings at every stage of design
- Ensuring early cooperation between all disciplines
- Faster testing and control of design decisions
- Ability to create cost estimates during the design phase
- Developing energy efficiency and sustainability decisions
- The result reached by the research; In general, the use of BIM in correct applications provides benefits to all project stakeholders in the construction and management processes.

Difficulties of Using BIM and Problems Encountered

The difficulties and problems in the use of BIM, determined as a result of a survey in which 31 contractor companies in the USA participated, are listed as follows (CRC Construction Innovation, 2007):

- Learning curve and lack of experienced personnel
- The cost of implementation is very high,
- Resistance of other project stakeholders (Contractor, Designer, etc.)
- Insufficiency of standards describing collaborative working and modeling processes,
- Not being able to work together,
- Insufficiency of legal and contractual agreements.

Literature Information on the Use of BIM in Rail Systems

In recent years, the Turkish Construction Sector has started to invest in BIM applications. Compliance with legal obligations regarding the use of BIM in construction projects is vital for Turkish companies to compete in the international market. World Turkish construction companies need to turn to the use of BIM to ensure their competitiveness and sustainability of performance. "The use of BIM is particularly demanded in our country in important public projects such as metro and airport. In countries where the use of BIM is encouraged at the national level, it is seen that property owners demand the use of BIM more in projects." (Ofluoğlu, 2021). This technology increases the efficiency of projects, reduces costs, strengthens communication and reduces risks. Therefore, the Turkish construction industry can maintain and strengthen its competitive advantage by complying with international standards and adopting innovative technologies. (Aladağ et al., 2016). "However, an industry-wide strategy is needed to facilitate this transition. Therefore; determining existing and new trajectories for further adaptation and applications is the first step in determining the current place of the Turkish Construction Sector in the global market." (Ezcan et al., 2013). Developments regarding BIM applications initiatives are observed in the Turkish Construction Sector, especially in rail system projects. The positive perspective on BIM technologies has brought to the agenda the tender studies that make BIM applications mandatory in government institutions, and various contractor and designer companies in the private sector are also encouraged in Turkey. In the process of transition to the BIM system, BIM infrastructure preparations and hardware development studies have begun. The advantages of the integration of this technology into railway projects have been started in the last few years for the development of standardization and the formation of BIM directives and protocols that will guide the use of BIM in many parts of the world. It enables collaboration, time saving, cost optimization, and prevention of conflicts between networks. It also provides optimization of management facilities, improvement of the quality of work, prefabrication before construction (Mounir et al., 2019).

BIM based railway construction organization integrates design optimization decision making. Its functions mainly include WBS decomposition and automatic linking method of engineering asset structure, location-based planning algorithm, progress monitoring method based on Internet of Things, and image progress display combined with BIM model and Gantt chart. The method creates a solid foundation for the precise management of railway construction. Designers can use BIM technology to optimize the allocation of construction resources. Then, with the help of network planning technology, they can combine modern BIM technology with traditional engineering methods. This will make full use of the relevant advantages and effectively solve the optimization problem. Thus, it can allocate construction resources more effectively and further reduce waste and construction costs (Jinghan et al., 2023).

BIM integration studies, which have started to come to the fore in recent years, are mainly used in the public sector. The pioneer of the BIM movement, which is making progress with government support in Turkey, is the KMM Metro Line project in the field of Rail System. It initiated the public enterprise movement by including BIM applications for the first time in the construction phase of the project. It was subsequently applied to other metro lines whose construction started.

Examining the Use of BIM in the Design Phase of Rail Systems in Turkey

"In Turkey, BIM application has become mandatory for all transportation projects as of 2022 (UAB, 2022). It has been decided by IBB to use BIM in metro construction projects before 2022 (IBB, 2017)." Emre et al. (2023) examining the use of BIM in the design phase of rail systems in Turkey started with the KMM Metro Line Project, one of the first exemplary projects where BIM was implemented, carried out by Istanbul Metropolitan Municipality in 2013. *Analysis of the use of BIM in the design process created an important reference point for subsequent projects. Based on the findings of the KMM Metro Line Project design phase, the use of the BIM system in the design phase will be examined, specifically for the ongoing MBE Metro Line Project. The benefits it provides and the problems encountered will be discussed.*

Kabataş-Mecidiyeköy-Mahmutbey(KMM) Metro Line Project

The first attempt to implement BIM technology, which emerged as an idea in 2012, in rail system projects in Turkey began with the decision to test it within the scope of the KMM Metro Line Project. This example represents an innovative change that has received government support for the application of BIM in a public project for the first time in Turkey.

- First Implementation and Integration Efforts: BIM was used in the design phase of the KMM Metro Line Project, which was first implemented by the Istanbul Metropolitan Municipality in 2013. BIM system studies have become the starting point of an initiative to integrate BIM-supported software with project management processes, beyond using them only as a tool in the project production process. Observation of BIM practices experienced during the Istanbul Rail System Department's UK Crossrail Metro Line tour in 2014 accelerated the sectoral establishment of the idea that the BIM system could be integrated with rail system projects in Turkey.

- Budget, project understanding, transparency and stakeholder participation advantages: With the application of BIM, the risk of budget exceedance in rail system projects is reduced, project understanding improves, transparency increases and stakeholder participation is ensured. As a result, more construction and maintenance can be accomplished with less public money. (EU BIM Task Group, 2017).
- The Crossrail Metro Line tour of the Istanbul Rail System Department in 2014 led to the acceleration of BIM integration in rail system projects in Turkey.

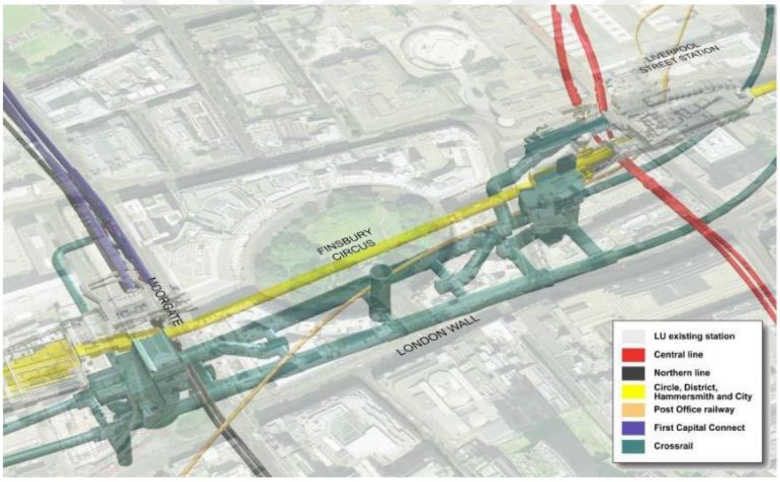

Figure 2: Crossrail metro line integration model (Taylor, 2013).

- Values Provided by BIM Adaptation in KMM Project: According to (Elif, A.,2018); It is the creation of a virtually realizable Metro Project that allows the development of design services by improving and optimizing the processes of design, construction, operation and decommissioning. By creating a digital model of BIM, it is planned that this model will support decision-making processes and respond to problems. The model needs to be managed together with the process, and at the same time, it must provide modeling and management services for two different uses, with the concept of "M" in the abbreviation BIM,meaning "Modelling/Management". Model management requires collaboration with all parties in program implementation, including the supply chain, this includes rail operators. Employer organizations that adopt the BIM system in this project will have the opportunity to better manage the constructed asset. These findings show the potential and advantages of BIM in Rail System Projects.

Use of BIM in the Design Phase of the MBE Metro Project which is the Continuation of the KMM Metro Line and is Still Under Construction

The design phase studies of the MBE Metro Project started with the presentation of the BIM Implementation Plan, BIM Production Process Procedure and Document Coding System. The methods to be applied throughout the design process, the standards and regulations to be referenced are described in these documents. The start of the BIM modeling studies in question took place in December 2017, according to official records.

Design studies in the MBE Metro Project are carried out as follows:

- Carrying out design studies for 5 stations between Bahçeşehir and Mahmutbey, which started at the preliminary project stage (Mahmutbey, Atatürk, Mass Housing, Theme Park, Hospital Stations).
- Model studies carried out by receiving architectural application projects in CAD environment for 11 stations between Esenyurt-Bahçeşehir-Mahmutbey; Preparation of fine business application models and E&M application models.
- Making model studies of line tunnels.
- Starting preliminary design studies as 3D models: Preliminary design studies for 5 stations located between Bahçeşehir and Mahmutbey have been started with 3D models. Model bases were developed and detailed in the final and application project stages.
- Taking into account the parameters affecting the design at the preliminary project stage, thanks to the 3D model: The first five stations are located in areas with dense construction due to their location. Location of the station structure, exit arms, shaft locations, etc. Since there are many parameters affecting issues such as, detailed preliminary project studies were carried out in the BIM environment. In this context; The platform tunnels of the stations, the layout of the concourse buildings and the relations of the tunnels with each other are shown in 3D.
- Ensuring coordination between relevant parties in the early stages: Since the company was the first contractor within the scope of work of the 1st stage of the rough construction design process of 11 stations between Esenyurt and Mahmutbey, preliminary, final and application project bases were prepared in 2D in CAD environment. Approved project studies were forwarded to the second contractor for three-dimensional digital construction of the designs. At this stage, the contractor was requested to perform specificationally defined current situation modeling. The completed stations were handed over to the finishing work and electromechanical work contractor so that they could start field work. İçtaş planned the design work program according to the stations whose reinforced concrete production would be completed fastest.
- Ensuring the integration of design and construction phases: In the current situation modeling process, 3D static models of the site-delivered stations were created with point cloud data using the laser scanning method. This method is used to detect manufacturing defects. It also shows that the design and construction phases work in an integrated manner.
- Identifying the problems in the project during the design process with the Navisworks program: 3D coordination of interdisciplinary design models can be used for both the design and construction phases. Architectural, static and electromechanical models prepared during the design phase were examined through Navisworks software for conflict checks. The detected conflicts were evaluated in coordination meetings held with the participation of design alternatives and project stakeholders developed in the digital environment before starting the manufacturing phase. These problems have been minimized.
- Determination of problems in the manufacturing phase by integrating architectural and electromechanical models in the Navisworks program: Models prepared for the disciplines (architectural and electromechanical) are integrated through the Navisworks software and prepared for conflict detection. In this digital environment, the models controlled and the detected conflicts are marked with the prepared model images called viewpoints. nwd with notes on the image. It is forwarded to the Contractor company by the Administration and Building Inspection Officer in file format. The contractor company directs the control and

editing works to the design subcontractors for 3D coordination. Thus, it takes precautions for disciplinary project problems that may arise during the manufacturing phase.

- The effect of using BIM in the design phase on time in alternative project production: 2D documents and sheets are produced from 3D models via Revit software. Creating plans and section sheets using 3D models is carried out more practically and faster with BIM software than doing the same process through CAD software. When the 1st and 2nd stages of the project are compared to each other, it has been experienced that the time spent on design and project production takes less time with the use of BIM. The effective use of time in the 2nd stage was evaluated as a usage advantage that increased the number of alternatives developed in the design phase.
- Developing design alternatives in fine works: In line with the decisions taken at the architectural design meetings, the works for the fine works will be manufactured with two different construction methods within the scope of 11 stations. It was also initiated by developing design alternatives for two stations (cut-cover and tunnel type).
- Line tunnel modeling using different software programs: Another design process study is the modeling of line tunnels. Modeling studies of line tunnels are modeled through Dynamo software, which works as an add-on with Revit, separately from the station architectural models.
- Ensuring the creation of cost estimation and material and quantity lists: By integrating the cost estimates made at every stage of the design phase with the BIM system, the use of BIM in 5D dimension is targeted. Detailed lists and quantities of the materials used in the project are obtained from BIM models.
- Ensuring the creation of cost data parameters: Various methods and techniques have been developed for project-specific quantity survey model studies. Cost estimation in 5D format can be achieved by creating parameters in which cost data is entered into the model elements, through progress payment models.
- Reduction of estimation times with software programs used in fine work cost estimates: With studies on the use of 5D BIM, cost estimates can be made quickly during the design phase through the MTO and QTO produced. With these studies, cost estimation studies for fine works can be carried out very quickly.
- Ensuring the creation of digital sheets: Another use that will speed up the construction phase is the creation of digital manufacturing visuals and location information sheets of the construction system design (Virtual Mockup). Virtual Mockup is based on the principle that implementation decisions during the construction phase are determined at the design stage. In use, it refers to the construction representation for certain selected field applications in a digital environment. The Contractor defines the conditions of this use in the BIM Implementation Plan as follows. (İçtaş, 2017): "Virtual mock-ups to be produced to analyze a complex building system in the model will be made on a station basis and 1 piece if needed.". For the station buildings, rendition will be made from 1 camera angle. It will be delivered in Jpeg format.

In summary, the design phase, which started with the presentation of the documents prepared during the contract phase for the MBE Metro Project, became the basic phase in which the BIM usage targets of the project were contractually concentrated. The design phase, which is linked to all other phases of the project, is a long usage period in which interdisciplinary coordination efforts are intensified, decisions affecting the construction and operation processes are matured and all kinds of model documents are produced. It was also stated in the interviews that the most effective use of BIM was made in the design phase of the project, which is currently under construction.

Benefits of Using BIM on the Design Process in the MBA Metro Line Project

MBE Metro Line, which is the continuation of the KMM Metro Line, is 18 km long with 10 station buildings. It is a Rail System Project, the construction of which started in 2017 and is still on going.

In the MBE Metro Project, a public project with the BIM concept, an interview was held with the employer (2 people), building inspection officer (consultant - 2 people), and the main contractor (2 people) regarding BIM Applications. Interview participants were tried to be selected in equal numbers from all project stakeholders (6 people in total).

Interviews were held at Halkalı MBE Metro Main Construction Site. Employer; MBE Metro Project Control Architect and BIM responsible Control Engineer within the Istanbul Metropolitan Municipality European Side Rail System Directorate. Project consultant; Architect responsible for the execution and follow-up of the BIM works of Emay International Engineering and Consultancy Inc. and MBE Metro Project Architectural Finishing Works Design Chief (Architect). Main Contractor; İçtaş İnşaat A.Ş. It was held between the BIM responsible (Civil engineer) and the BIM Chief (Civil Engineer) project parties (6 people in total). A total of 15 questions asked to the parties regarding the use of BIM at all stages of the project are as follows:

1- What is the place and importance of the BIM system in the MBE Metro Project?
2- How was the BIM process and adaptation achieved in the MBE project?
3- What are the most significant managerial and organizational changes made in your company/institution in the transition to BIM?
4- What are the advantages and disadvantages of BIM in the MBE Metro Project?
5- What will be the benefits of the BIM process continuing the life cycle from design to operation in metro projects?
6- Which of the project management processes do you think the use of BIM affects most positively and which negatively? From where?
7- Could you explain how the use of BIM affects the cost, time and quality performances of the project?
8- How has the sectoral resistance to BIM affected the metro projects and/or what action was taken against the resistance?
9- What benefits will BIM and life cycle process in public institutions provide to the smart city and the digitalization of the city?
10- What are the biggest difficulties you encounter in the adaptation of traditional methods to the BIM process in your company/institution?
11- Has any training or adaptation program been implemented for the personnel working in your company/institution during the BIM adaptation process? What kind of programs do you think will facilitate the adaptation process?
12- Do you find the adaptation of the designers/project developers/production companies in the sector to the process sufficient? What were the difficulties you experienced with the contractors you worked with during this process?
13- Does your company/institution ensure that you adapt to new technologies that develop throughout the process and update your techniques in this direction?
14- In line with your experience, what are your managerial suggestions and recommendations for effective use of the system in rail system projects tendered with BIM?

15- Could you explain the benefits of using building information modeling in the Design Process with reference to BIM Handbook (2011)?

As a result of the agreement made between these relationships, the efficiency of the BIM process in the Design Process was examined on a project-specific basis, with reference to the BIM Handbook (2011).

- Visualizations of the design can be made more accurately and at earlier stages (BIM Handbook, 2011). In the MBE Metro Project, the designs were prepared and delivered using the BIM infrastructure as a tender annex in 2017, the tender date. As of the start of the project, these designs have undergone many revisions. However, thanks to 3D models and imaging opportunities, designers and other teams contributing to the design process can easily understand the structures, routes and changes that the designs undergo from the tender process to the construction process.
- Automatic, model-related information updating based on changes made in the design (BIM Handbook, 2011). Metro projects are among the projects with the most multidisciplinary interaction. Therefore, changes made in the design must be quickly visible to other units, especially if manufacturing has started. In this context, with the use of the BIM ecosystem and common database, each stakeholder has the opportunity to access the current project without intermediaries within their authority.
- Ability to produce accurate and compatible 2D drawings at every stage of design (BIM Handbook, 2011). Thanks to the system and associated visualization tools included in the use of BIM, the transition from draft drawing to presentation-ready drawing has been accelerated. Also presentation, narration etc. In cases where it is necessary to support drawings, the current design can be accessed quickly.
- Early ensuring cooperation between all disciplines (BIM Handbook, 2011). In the MBE Metro Project, there are institutions/companies involved in the design process and professionals from different disciplines working under them. Employees from different disciplines and different institutions/companies can interpret projects without even having to come together physically. Transmitting comments and receiving feedback to these comments is provided by BIM. In addition, it is possible for the disciplines involved in the design process to work simultaneously thanks to the central model and cloud systems.
- Quick testing and checking of design decisions (BIM Handbook, 2011). Designs include passenger numbers, fire escape scenarios, etc. in the MBE Metro Project. It may undergo minor or major changes depending on many reasons. However, in a situation where design processes are carried out using traditional methods other than BIM, this means that many separate drawings, 3D visualizations and calculations change. With BIM, these changes are made automatically. More control is provided over the mechanisms that will affect the process, such as the impact of the design decision on other volumes with cross sections and the calculations required to ensure compliance with the standards.
- Creating cost estimates at the design stage (BIM Handbook, 2011). The placement of costly electromechanical systems must be re-evaluated in each design revision, they contain structural elements that require high engineering, and the project financier is public resources, etc. For these reasons, cost has the power to highly affect design decisions in metro projects. In this context, cost estimates are created at each step so that a decision can be made. In the MBE Metro Project, each element of the digital twins is costed with BIM. The financial consequences of numerical or structural changes of these elements are calculated.

- Developing energy efficiency and sustainability decisions (BIM Handbook, 2011). In the MBE Metro Project, calculations that can be evaluated within the framework of sustainability and energy efficiency during the operation phase, following the design and construction processes, are made using BIM models and tools within the system. These calculations include operational costs, optimal placement of energy resources and equipment, and scenarios based on population change.

Challenges and Problems in Using BIM in MBE Metro Project

According to the answers received as a result of the interviews with MBE Metro Project BIM users, it was stated that although the application has advantages for the users and the project, some inadequacies and deficiencies in use turned into problems in the project processes.

- Lack of qualified personnel with knowledge and skills: The difficulty of finding personnel experienced in BIM and the competitiveness among companies within the sector cause rapid personnel turnover. This resulted in the risk of these companies losing talented and experienced employees in the field of BIM, causing various deficiencies and losses in the organizational structures of the project teams over time. The reason why we cannot find experienced and talented personnel in this field is the complexity of BIM and the special skill set it requires. Competition between companies within the industry creates greater pressure to attract and retain qualified employees. In this case, companies often face the risk of losing experienced personnel to rival companies.
- The high cost of BIM software and hardware: The software used in the BIM process causes small and medium-sized companies, especially, to not be able to allocate such a budget. This creates an obstacle for BIM to become a universal system.
- Incompatibility and data collaboration problems may occur when combining and updating BIM models used by different disciplines.
- It may take time for people and institutions accustomed to traditional methods to get used to the idea of integrating the BIM system into project production and management processes. Initially, the concept of BIM was generally viewed as a side goal of the project, rather than a system integrity covering all project management processes. However, this attitude towards the use of BIM in later project stages may change over time. This has been identified as an obstacle in the project adaptation process. All project stakeholders have encountered people and attitudes that resist BIM practices during their adaptation processes.
- By the nature of BIM, the fact that it is a complex process and requires the cooperation of many stakeholders from different disciplines (architecture, engineering, construction, etc.) makes it difficult to determine standards and regulations. However, there are some standards and guides on BIM developed by various national and international organizations. For example, organizations such as the Institute of Construction Industrial Engineers (ASCE), the American Association of Civil Contractors (AGC), and the American Institute of Architects (AIA) have published guidelines and standards on BIM. Additionally, the International Standards Organization (ISO) is also working on standards for BIM. However, these standards often may not fully meet the needs of a particular project or may have limited applicability. Therefore, it is common to use different approaches and practices in different metro projects. This may require stakeholders using BIM to develop their own methods and procedures, taking into account project-specific needs and requirements.
- Managing and analyzing BIM models in large and complex metro projects sometimes makes things difficult in terms of hardware and technical aspects. Problems such as

large file sizes and difficult to control models may occur. Ensuring the security of sensitive information contained in BIM models is an important issue. In the use of BIM, data security should be defined within strict limits along with quality control processes.

- It is also a problem that the potential of BIM is not used efficiently at every stage of the project and is used only at the design stage. A BIM model contains a lot of information that can be useful in the business process, and this knowledge should continue to be used.
- In metro projects, the Employer is contractually defined as the owner of the legal rights and uses of the project. However, subcontractor confidentiality problems were encountered during the design phase, such as protecting private information regarding the use of patented Revit smart objects and model production methods and not wanting to share it (knowhow). It is stated in the technical specification article to prevent this problem as follows (IBB, 2017):
    - The Building Inspector/Administration owns all CAD, BIM, Special simulation and facility data produced for this project.
    - Building Inspection Officer/Administration can use these documents wherever they want.
    - The Contractor cannot charge an additional fee for this.

For this reason, the technical specification automatically eliminates the risks of keeping the produced models and data confidential. The confidentiality principles of the companies have caused business disruptions in measuring the model quality and auditing the projects within the scope of this work. Failure to provide model access does not allow data access in a collaborative working environment, which is one of the advantages of BIM, at the desired time and in a way that serves the desired purpose. The companies' attitudes towards sharing the data they produce were shown among the reasons for trying to cooperate with different subcontractors and not continuing to work with some design companies.

Results

In the KMM Metro Project and its sequel, the MBE Metro Line Project, the benefits of BIM applications in the design details can be seen;

- It saves time and resources by automating the design and drawing processes and minimizes errors and contradictions in this process,
- Optimizes workflow,
- It facilitates communication between different disciplines,
- Provides a better understanding of the project thanks to 3D modeling,
- Provides more accurate cost estimates by detecting conflicts in different disciplines in advance,
- It enables the development of more detailed and coordinated designs in terms of quality,
- Optimizes building performance and sustainability,
- Appears to increase user experience and building functionality.

Moreover,

- BIM can make visualizations more accurately and at earlier stages, providing automatic updates based on changes made,
- Producing accurate and compatible 2D drawings,
- Ensuring early collaboration between all disciplines,
- Ability to quickly test and control design decisions

- Features such as improving energy efficiency and sustainability decisions add more value to the design process. It is necessary to achieve better quality and sustainable results by increasing efficiency in the design process. Therefore, it is understood that construction companies should give importance to digitalization, especially BIM, which is necessary for this sector, for their future sustainability.

In order for the use of BIM in question to become widespread and to fully utilize its potential, its mandatory implementation should be made in all public tenders, as in large-scale rail system projects. Investing in training and skill development programs. Making BIM software and hardware more affordable. Conducting data collaboration and standardization studies. Developing technical infrastructure. BIM should be used throughout the entire project life cycle and is recommended.

References

Azhar, S., Khalfan, M., & Maqsood, T. (2011). Building information modeling (BIM): now and beyond. *Australasian Journal of Construction Economics and Building*, *12*(4), 15-28.

Aladag, H., Demirdogen, G., & Isık, Z. (2016). *Building information modeling (BIM) use in Turkish construction industry. Proceedings of World Multidisciplinary Civil Engineering-Architecture-Urban Planning Symposium*, Istanbul, pp. 174-179.

CRC Construction Innovation. (2007). *Adopting BIM for facilities management: solutions for managing the Sydney Opera House*. Cooperative Research Center for Construction Innovation.

Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2011). *BIM handbook: a guide to building information modeling for owners, managers, designers, engineers and contractors* (2nd ed.). John Wiley & Sons.

EU BIM Task Group (2017). *Handbook for the introduction of Building Information Modelling by the European Public Sector: what is 'BIM' to the public sector stakeholder*. European Union. http://www.eubim.eu/wp- content/uploads/2017/07/EUBIM_Handbook_Web_Optimized.pdf

Ezcan, V., Goulding, J. S., Kuruoglu, M., & Rahimian, F. P. (2013). *Perceptions and reality: revealing the BIM gap between the UK and Turkey*.

Elif, A. (2018). *A case study and managerial suggestions on the transition processes to Building Information Modeling in the rail system sector in Turkey* [Master thesis]. Istanbul Technical University.

Emre A., & Salih O. (2023) Sustainable facility management in metro stations BIM supported digital twin applications. *Building Information Modeling*, *5*(1).

Fazli, A. F., S., Enferadi, M., Fazli, M., & Fathi, B. (2014). Appraising effectiveness of Building Information Management (BIM) in project management. *Procedia Technology*, *16*, 10.

IBB (2017). *Building Information Modeling YBM Technical Specification Draft.* Istanbul Metropolitan Municipality.

Jinghan, Z., Jiayu, L., Beisheng, L., Hui, L., & Wei, Y. (2023). *The design and application of BIM + refined management and control platform for the Jingxiong railway bridge*. China Academy of Railway Sciences Corporation Limited.

Kıvırcık, I. (2016). *An Investigation into the building information modeling applications in the construction project management* [Master thesis]. Istanbul Technical University.

Meadati, P. (2009). *BIM extension into later stages of project life cycle.* Southern Polytechnic State University.

Mounir, B., Abdelmajid, E., & Hassan, M. (2019). Railway information modeling - a review of railway project management integrating BIM. *International Journal of Railway*.

Ofluoğlu, S., (2021). BIM supported designs create more sustainable buildings. *Mimar Sinan Fine Arts University Yapı Magazine*, 42-46.

Özorhon, B. (2018). *Building information modeling: IBB Anatolian side rail system projects.* Abacus Publishing House.

Rüveyda, K., & Çağrı, Ü. (2022). A case study on BIM-based project management and its applications in Turkey. *Academic Journal of Social Research*, *10*(133), 8-25.

Rokooei, S. (2015). Building information modeling in project management: necessities, challenges and outcomes. *Proceedings of 4th International Conference on Leadership, Technology, Innovation and Business Management*, pp. 87-95.

Taylor, M. (2013). Crossrail: a case study in BIM. *Proceedings of Lake Constance 5D Conferance*.

URL-1 (2024). https://kelarpacific.com

UAB (2023). *Ministry of Transport and Infrastructure, BIM Technical Specifications and Tender Documents.* https://www.uab.gov.tr/uploads/pages/stratejik-yonetim/bim-teknik-sartnamesi-rev-no-03-02-09-2022.pdf

Calculation of the Productivity of Construction Gypsum Plaster Worker Using Support Vector Machine Algorithm

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Abstract

Calculating the productivity of workers in traditional construction projects can be a daunting and time-consuming task. However, thanks to the advancements in technology and scientific research, measuring labor productivity can be automated. Therefore, this study aims to determine the productivity of gypsum plaster workers by collecting motion data with a sensor on their arms and using the support vector machine algorithm for analysis. Based on the estimation results, motion productivity is determined by calculating the ratio of the worker's working time to the total time. On the other hand, labor productivity is calculated by determining the ratio of the amount of work completed to the product of the number of workers and the total working hours. Finally, theoretical productivity is calculated by dividing motion productivity by the calculated labor productivity. According to the results of the analysis, whether the worker is working or not has been estimated correctly by 95.8%. On the other hand, the mean daily theoretical productivity has been determined to be 10.20 m2/man-hour. In this way, workers' activities can be automatically detected with a certain accuracy and their productivity can be calculated. This helps in the effective management of the construction site.

Keywords: *construction technology, worker activities, support vector machine, worker productivity estimation, artificial intelligence.*

Introduction

The construction industry is a vital sector in the global economy, but it often faces challenges such as low productivity resulting in low quality, high costs, and time overruns. Measuring and estimating labor productivity in this industry can be challenging due to the variability of worker productivity depending on the labor force used. This creates difficulties in accurately estimating the labor productivity of the construction sector. In construction planning and process, measuring and estimating labor productivity is crucial. Determining worker productivity status helps manage the process effectively. Incorporating new technologies and advanced methods to measure and forecast labor productivity is crucial for addressing concerns and improving the construction industry's efficiency and effectiveness. The integration of modern technology is key to enhancing labor productivity in construction, as per various studies. According to a study in the USA, the construction sector has one of the lowest scores on the digitalisation index (Manyika et al., 2015). Today, with the convenience of digitalisation, scientific studies have been conducted to integrate technology into the construction industry (Akinosho et al., 2020;

Begić & Galić, 2021; Calvetti et al., 2020; Xu et al., 2021). In 2018, McKinsey & Company published a report stating that the construction industry will increasingly rely on advanced technologies. These technologies encompass digital twins, artificial intelligence, the Internet of Things (IoT), 3D printers, robotics, real-time monitoring and control systems, document management, and 3D modelling and BIM technologies (Blanco et al., 2018). The integration of cutting-edge technologies such as artificial intelligence, internet of things, real-time monitoring, and control can serve as a catalyst for automating the recognition of labor activities and calculating labor productivity in the construction sector. This advancement has the potential to significantly streamline processes and increase efficiency on construction sites.

In 2016, a study by Akhavian and Behzadan explored the use of an artificial intelligence model that could automatically detect worker movements using data from smartphones. The study analysed the effectiveness of various AI models, including artificial neural network, decision trees, nearest neighbour, logistic regression, and support vector machines, in identifying the time spent on each activity, including idle time. The findings suggest that utilizing machine learning techniques to analyse worker activity and time can be a valuable tool in evaluating productivity. The models created by the study can be directly applied to measure productivity (Akhavian & Behzadan, 2016). Sanhudo et al. (2021) conducted a thorough study to assess the accuracy and usability of accelerometer data and machine learning algorithms in categorizing construction workers' activities. To achieve this, a realistic circuit was created to capture ten distinct activities that occur during wall building in a controlled laboratory environment. The workers were outfitted with accelerometer sensors to collect data for each activity. The data collected from the sensors were used to train and compare 13 different machine learning algorithms including decision tree, k nearest neighbour, logistic regression, multilayer perceptions, and support vector machines (SVM). Additionally, ensemble machine learning algorithms such as random forest, extreme random trees, adaptive boosting, and gradient boosting machines were also employed for comparison. (Sanhudo et al., 2021). In Son's (2017) study, the author examined the possibility of measuring labor productivity by calculating the ratio of active working hours to total working hours, based on data obtained from workers. To enhance productivity in a construction site setting, the author suggests that gathering physical and location data every second can be beneficial since productivity data can be difficult to collect and measure in real-time. The study defines labor productivity as the ratio of time spent on direct work by a construction worker to total work time. Furthermore, the study focuses on measuring the individual productivity of each worker rather than the project's overall productivity (Son, 2017).

The recognition of construction activities involves the utilization of specialized equipment. Specifically, the process entails the measurement of acceleration, angular velocity, and gravitational forces using a combination of three sensors - accelerometer, gyroscope, and magnetometer. The data obtained from these sensors are then analyzed to identify the specific construction activities taking place. It is worth noting that the accuracy of the results is dependent on the quality of the equipment used and the expertise of the personnel involved (Fang et al., 2016). Some studies have used only accelerometer data for activity recognition in construction work (Joshua & Varghese, 2014; Ryu et al., 2019; Sanhudo et al., 2021). The inclusion of both accelerometer sensors in the X, Y, and Z axes and gyroscope sensors that measure angular velocity allows for the recognition of construction activities. These sensors can detect rolling, pitching, and yawing movements in the three axes, thereby expanding the range of worker activity movement characteristics. As a result, it becomes simpler to differentiate between each activity (Zhang et al., 2018). Therefore, some studies have used a combination of accelerometer and gyroscope data for construction worker activity identification analyses (Akhavian & Behzadan, 2016, 2018; Zhang et al., 2018). In addition Garcia-Gonzalez et al. (2020) stated in their study that gravitational force measurements data collected with the magnetometer sensor would be useful to be used with other sensors in the recognition of labour activities. The aim of this study is to examine the information collected from employees through accelerometer, gyroscope, and magnetometer sensors. Through the use of artificial intelligence models, their movements and behaviours will be identified, enabling the computation of worker productivity to be automated.

Research Methodology

As technology advances, data collection systems are becoming increasingly efficient at measuring labor productivity. Compared to traditional methods like direct observation or surveys, which can be time-consuming, tedious, and prone to errors, these automated systems offer a more effective solution. In light of this, our study seeks to utilize machine learning to analyze data collected via sensors attached to workers' arms, providing predictions of their activities and accurately calculating productivity. This study employs the support vector machine (SVM) machine learning method to accurately predict the work status of a Gypsum Plaster worker. To achieve this, we followed a step-by-step approach illustrated in the Figure 1 flowchart. We began by collecting and categorizing raw data from the worker at the construction site. Subsequently, we meticulously processed, sorted, and extracted its essential attributes to ensure the data was model-ready. The initial step involves dividing the data into two distinct sets: training and test data. Subsequently, the training data will be meticulously analysed to determine the success of predictions in comparison with the test data. Once this is accomplished, the prediction model will be integrated with the data collected during the day to forecast worker activities. Finally, the theoretical efficiency will be calculated based on movement efficiencies and worker efficiencies.

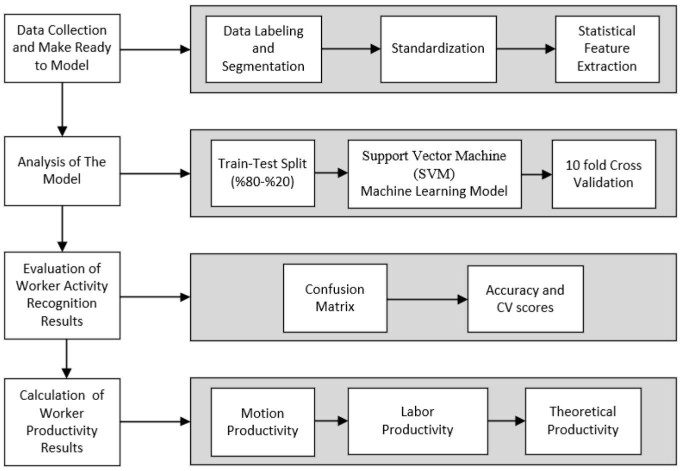

Figure 1: Flowchart for the study.

As part of this study, information regarding gypsum plaster activities was gathered from the construction of a reinforced concrete school. A sensor was affixed to the craftsman handling the plastering task, as depicted in the Figure 2, and 3-axis acceleration, gyroscope, and magnetometer data were recorded throughout the process. Data was collected throughout the day at 2-hour intervals between 8:00-10:00, 10:00-12:00, 13:00-15:00 and 15:00-17:00. To label the data according to the activity it belonged to, the workers' work at the construction site was observed and noted. The data was gathered with the assistance of a data acquisition device and subsequently analyzed utilizing the Python programming language. To elevate the predictive potential of the machine learning models, the data underwent normalization through the z-score standardization method subsequent to its collection.

Figure 2: Data collection with sensor attached to the gypsum plaster workers' arm.

Initially, the data will undergo separation and feature extraction processes to obtain the necessary features for prediction. The data obtained were partitioned into windows of a specific duration, and the statistical characteristics of the data within each window were computed. For this study, a window size of 4 seconds and an overlap rate of 75% were chosen. The 4-second windows were then shifted, as depicted in the Figure 3, and all windows were computed with a 75% overlap. The new features were calculated by analyzing the statistical properties of the data within the specified windows. These statistical features include the sum, median, mean, length, standard deviation, variance, square root (quadratic) mean, maximum and minimum of the values in each window of the data in the x, y, and z directions taken from the accelerometer, gyroscope, and magnetometer sensors as shown in Table 1. A total of 81 variables were created using this method. After this process, the new data obtained will be ready to be used for the model.

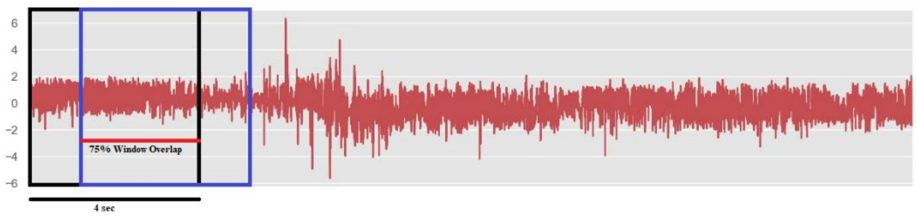

Figure 3: Data segmentation process.

Table 1. Features and description created with statistical feature extraction.

Statistical Features Names	*Description*
Sum values	Calculates the sum over the seperated windows values
Median	Calculates the median the seperated windows values
Mean	Calculates the mean the seperated windows values
Length	Calculates the length the seperated windows values
Standard deviation	Calculates the standard deviation the seperated windows values
Variance	Calculates the variance the seperated windows values
Root mean score	Calculates the quadratic mean the seperated windows values
Maximum	Calculates the maximum value the seperated windows values
Minimum	Calculates the minimum value the seperated windows values

The data that was prepared for the model was initially divided into 80% training data and 20% test data. The training data was then analyzed, and prediction accuracies were calculated by comparing them with the test data. For this study, the machine learning model used was the Support Vector Machine (SVM) algorithm. After developing the SVM model, we utilized the 10-fold cross-validation technique to ensure the model was unbiased and minimize data bias. This involved dividing the training data into 10 layers and using one layer as validation data while the remaining 9 layers were used as validation-training data. The prediction accuracy values were averaged for each layer to calculate the cross-validation prediction values.

The aim of gypsum plastering is to gauge worker productivity using state-of-the-art Artificial Intelligence techniques. In order to achieve this, data was gathered from accelerometers, gyroscopes, and magnetometers along the x, y, and z-axes over an 8-hour period. However, only the 2-hour measurements were scrutinized. For the remaining 6 hours, a Support Vector Machine (SVM) learning algorithm was employed to predict the measurements and create a model for analysis. The resulting model was then used to assess overall productivity. In order to utilize the SVM machine learning model to forecast construction activities, it is essential to prepare the data collected throughout the day in two-hour intervals. Once the data is prepared, it is analysed each two-hour measurement using the prediction model to obtain anticipated activity times. These predicted times will then be compared to the observed activity times. To assess the effectiveness of each activity during the 2-hour working periods, we will calculate their motion productivity based on the predicted and observed values. Motion productivity will be calculated by dividing the working time of each activity by the total time, which includes both working time and waiting time. The formula for calculating motion productivity is shown in Equation 1.

$$Motion\ Productivity\ (\%) = \frac{Working\ Time\ (sec)}{Total\ Time\ (sec)} * 100 \tag{1}$$

The workers' motions and the amount of work done in 2-hour periods were measured at construction sites. This is done to calculate labor productivity values during these periods. Equation 2 is used to calculate labor productivity values.

$$Labor\ Productivity = \frac{Total\ Output}{Total\ Input} \tag{2}$$

After calculating motion and labor productivities, the theoretical productivity values that a worker would achieve if it were worked at full capacity were calculated according to equation 3.

$$Theoretical\ Productivity = \frac{Labor\ Productivity}{Motion\ Productivity} \quad (3)$$

Results and Discussions

A SVM machine learning model was designed to accurately detect the working status of a gypsum plaster at a construction site. The model was meticulously scrutinized, and the resulting confusion matrices have been conveniently presented in Figure 4. The analysis reveals that the model was able to predict with 96% accuracy (704 out of 740) the total waiting activities. Furthermore, the model accurately predicted 97% (622 out of 644) of the total gypsum activities.

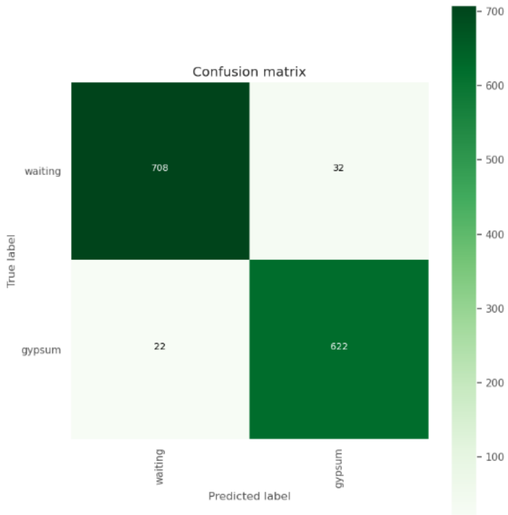

Figure 4: Confusion matrix of SVM model.

Confusion matrices are a useful tool to determine the predictive success of any activity in SVM model. In this study, the predictive success of the SVM model is presented in the table 2, considering the overall prediction success. Accuracy scores of the models were evaluated in two ways. Firstly, the model was assessed using training accuracy scores, and then accuracy values were generated using the 10-fold cross-validation (CV) technique, which is a more accurate and robust method for evaluating models. Upon thorough analysis of the results, it has been determined that the CV accuracy value of the model is considerably lower by a factor of 10. Nonetheless, it has been discovered that an evaluation based on these values would yield greater accuracy and robustness. Consequently, it has been observed that the SVM model boasts an impressive accuracy rate of 95.8% in predicting the working status of a plaster worker.

Table 2. Results of activity recognition.

	Training Accuracy	10-fold CV Accuracy	Number of Data
SVM (C:100)	0.961	0.958	1384

Once the prediction results of the SVM model were deemed acceptable, the data collected throughout the day was prepared and fed into the SVM model to obtain the prediction results.

During the data collection process from sensors, the system also kept track of the time period in which the master worked on a particular job and the amount of work he accomplished. The aim is to calculate workers' estimated productivity throughout the day and compare it with their labor productivity. The results are presented in a Table 3. It shows that the observed and predicted working hours and motion productivity are very similar in all working hours. The estimated motion productivity during 8-10, 10-12, 13-15, and 15-17 was approximately 47%, 79%, 88%, and 63%, respectively.

Table 3. Results of motion productivity.

Activity	Working Hours	Work	Time (sec)		Motion Productivity (%)	
			Predict	Observed	Predict	Observed
Gypsum Plaster	8-10	Gypsum	3257	3231.1	47.05	47.41
		Waiting	3665	3583.69		
	10-12	Gypsum	5494	5430	79.44	79.74
		Waiting	1422	1379.5		
	13-15	Gypsum	6036	5954.89	87.59	87.73
		Waiting	855	833.048		
	15-17	Gypsum	4336	4282.88	62.68	62.88
		Waiting	2582	2528.43		

Theoretical productivities were calculated by dividing measured labor productivity by calculated motion productivity. The Table 4 shows the theoretical productivity of gypsum activity for each time frame. Theoretical productivity indicate how productive activities would be if they worked continuously during the designated working hours, without any waiting periods. Based on the results, the theoretical productivities of the activities were calculated to be 8.50, 11.33, 7.42, and 13.56, respectively.

Tablo 4. Results of theoretical productivity.

Activity	Working Hours	Labor Productivity (m2/1 man-hour)	Motion Productivity	Theoretical Productivity	Unit
Gypsum Plaster	8-10	4.00	0.4705	8.50	m^2/man*hour
	10-12	9.00	0.7944	11.33	
	13-15	6.50	0.8759	7.42	
	15-17	8.50	0.6268	13.56	

When the productivity calculations of the gypsum plastering activity are analysed separately, the theoretical productivity and partial productivity of the construction activities in each time zone are visually evaluated and how much the workers work in proportion to their daily working capacity is shown in Figure 5. Based on the findings, the gypsum activity demonstrated higher productivity during the 10-12 and 15-17 hour periods compared to other hours of the day. When comparing productivity values during these two periods, the labor productivity were found to be almost equal. However, the theoretical productivity between 15-17 hours is quite high. In other words, it is seen that the laborer works less in terms of working hours in this time period. On the other hand, when the productivity values between 8-10 and 13-15 hours are compared, the theoretical productivity is almost the same in these hours. It was found that the labor productivity value was higher between 13-15 hours of work. This means that although the worker's working capacity was similar during these time periods, they worked more in terms of working hours between 13-15 hours. In consideration of the daily productivity of a gypsum plaster worker, it is observed that should the worker continue to work without any breaks, the labor productivity can be increased from 7 m2/man*hour per day to a theoretical productivity of 10.20 m2/man*hour. In light of the fact that laborers are required to take a half-hour break prior to and following lunch over the course of the day, the maximal theoretical efficiency in gypsum plastering activity computes to 8.93 m2/man*hour.

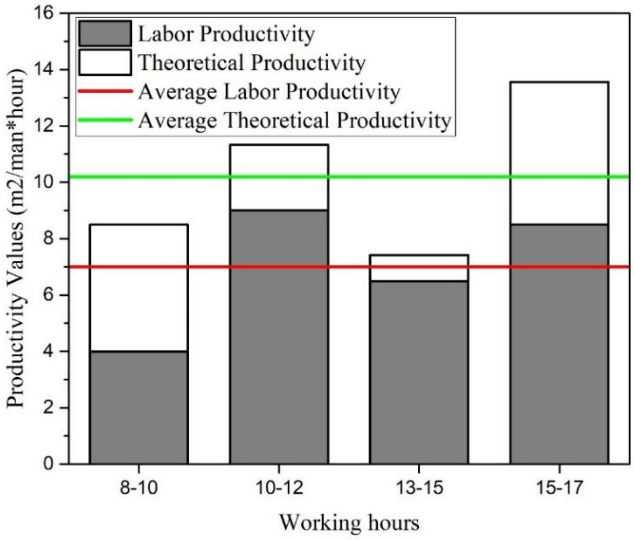

Figure 5. Daily productivity values of the worker.

Conclusion

Automatically recognizing labor activities and measuring productivity in real-time can have a positive impact on increasing productivity and aiding project managers in site control and management. By using sensors to capture motion data, the SVM algorithm analyse the data and determine with 95.8% accuracy whether a worker is present and working on the construction site. By monitoring the workers in real-time, it becomes possible to have better control over the construction site. Automatic recognition of their activities also allows for the calculation of their motion productivity. The theoretical efficiency is determined by comparing the labor productivity obtained from the construction site with the motion productivity. The concept of theoretical productivity pertains to a worker's ability to perform tasks based on their movements. In essence, enhancing labor productivity can be achieved by precisely gauging the work performed by workers and their theoretical productivity. This approach will enable us to identify the opportune time and method to augment worker productivity. Through this, we can optimize labor productivity at construction sites and guarantee more streamlined and effective project management. In this case, the theoretical and partial productivity calculations of the activities should be calculated on the basis of the workers working on the basis of the activity, which will lead to more realistic and applicable results. Since the productivity of each activity will vary depending on the worker, it is clear that the productivity of which activity can be increased or not can vary. As a result, making an automatic productivity calculation based on the worker will have a significant positive effect on productivity.

References

Akhavian, R., & Behzadan, A. H. (2016). Smartphone-based construction workers' activity recognition and classification. Automation in Construction, 71, 198–209. https://doi.org/10.1016/j.autcon.2016.08.015.

Akhavian, R., & Behzadan, A. H. (2018). Coupling human activity recognition and wearable sensors for data-driven construction simulation. *Journal of Information Technology in Construction*, *23*(1), 1–15.

Akinosho, T. D., Oyedele, L. O., Bilal, M., Ajayi, A. O., Delgado, M. D., Akinade, O. O., & Ahmed, A. A. (2020). Deep learning in the construction industry: A review of present status and future innovations. *Journal of Building Engineering*, *32*, 101827. https://doi.org/10.1016/j.jobe.2020.101827

Begić, H., & Galić, M. (2021). A Systematic Review of Construction 4.0 in the Context of the BIM 4.0 Premise. *Buildings*, *11*(8), 337. https://doi.org/10.3390/buildings11080337

Blanco, J. L., Mullin, A., Pandya, K., Parsons, M., & Ribeirinho, M. J. (2018). Seizing opportunity in today's construction technology ecosystem. *McKinsey & Company*. https://stevenssa.com/wp-content/uploads/2020/02/mckinsey-and-company.-seizing-opportunity-ın-today%e2%80%99s-construction-technology-ecosystem.pdf

Calvetti, D., Mêda, P., Chichorro Gonçalves, M., & Sousa, H. (2020). Worker 4.0: The Future of Sensored Construction Sites. *Buildings*, *10*(10), 169. https://doi.org/10.3390/buildings10100169

Fang, Y., Cho, Y. K., & Chen, J. (2016). A framework for real-time pro-active safety assistance for mobile crane lifting operations. *Automation in Construction*, *72*, 367–379. https://doi.org/10.1016/j.autcon.2016.08.025

Garcia-Gonzalez, D., Rivero, D., Fernandez-Blanco, E., & Luaces, M. R. (2020). A Public Domain Dataset for Real-Life Human Activity Recognition Using Smartphone Sensors. *Sensors (Basel, Switzerland)*, *20*(8). https://doi.org/10.3390/s20082200

Joshua, L., & Varghese, K. (2014). Automated recognition of construction labour activity using accelerometers in field situations. *International Journal of Productivity and Performance Management*, *63*(7), 841–862. https://doi.org/10.1108/IJPPM-05-2013-0099

Manyika, J., Ramaswamy, S., Khanna, S., Sarrazin, H., Pinkus, G., Sethupathy, G., & Yaffe, A. (2015). *Digital America: A Tale of the Haves and Have-Mores.* McKinsey Global Institute. https://doi.org/10.1787/888932360119

Ryu, J., Seo, J., Jebelli, H., & Lee, S. (2019). Automated Action Recognition Using an Accelerometer-Embedded Wristband-Type Activity Tracker. *Journal of Construction Engineering and Management*, *145*(1), 4018114. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001579

Sanhudo, L., Calvetti, D., Martins, J. P., Ramos, N. M., Mêda, P., Gonçalves, M. C., & Sousa, H. (2021). Activity classification using accelerometers and machine learning for complex construction worker activities. *Journal of Building Engineering*, *35*, 102001. https://doi.org/10.1016/j.jobe.2020.102001

Xu, Y., Zhou, Y., Sekula, P., & Ding, L. (2021). Machine learning in construction: From shallow to deep learning. *Developments in the Built Environment*, 100045. https://doi.org/10.1016/j.dibe.2021.100045

Zhang, M., Chen, S., Zhao, X., & Yang, Z. (2018). Research on Construction Workers' Activity Recognition Based on Smartphone. *Sensors (Basel, Switzerland)*, *18*(8). https://doi.org/10.3390/s18082667

Digital Twin in Construction Industry: A Bibliometric Review

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Abstract

Digital twin (DT) opens up exciting possibilities for the construction industry. The integration of machinery, sensors, and intelligent systems into construction processes has evolved with technological advancements. A DT digitally represents real assets, serving as a virtual illustration with real-time data for prediction, optimization, monitoring, and enhancing efficiency. In many applications, DT is currently a significant and developing trend. In this regard, a great deal of study has been focused on DT. The purpose of this study is to review the literature on DT in the construction sector and investigate the potential of the DT to determine the research trends. The current literature on DT in the construction industry is examined in this study by bibliometric analysis. Publications related to DT were identified and retrieved from Scopus. Subsequently, bibliometric analysis was conducted using VOSviewer. The results showed that over time, keywords change from covering broad topics such as BIM, construction and industry 4.0 to increasingly specialized and in-depth topics such as predictive maintenance, ontology and semantic web. Additionally, there are other points related to the computer and mechanical sectors which may stem from the fact that advancements in technology and informatics significantly influence the concept of a DT applied in construction.

Keywords: *construction industry, digital twin, potential of digital twin.*

Introduction

The idea of the DT is gaining attraction and growing popularity with the advancement of information technology and data delivery (Wang et al., 2021; Liu et al., 2021; Kim & Ham, 2022). As a result, research on this topic has increased lately (Sun et al., 2022). Almatared et al. (2022) highlight that the AEC sector is adopting DT technologies progressively as a result of their benefits, including enhanced production and efficiency. Grieves introduced DT technology in 2003, creating a dynamic virtual representation reflecting real-world characteristics using real-time sensor data (Fuller et al., 2020; Liu et al., 2021; Teizer et al., 2022). Rasheed et al. (2020) identify the 3 primary components of the DT as the real world twin, the virtual world twin and the relationship that links the twins with the transfer of data and information. The goal of developing a DT is to offer knowledge and understanding for decision-making and action regarding the physical twin (Sun et al., 2022). DT can assist in the planning, monitoring, execution, identification of risks, enhancements, optimization of performance, maintenance and forecasting future needs (Zhang et al., 2021). Therefore the application of DT can offer significant advantages to the field of architecture (Lu et al., 2020a; Wang et al., 2022). It contributes to minimizing the lasting effects of buildings and enhances the efficiency in the construction (Boje et al., 2020). Si et al. (2023) suggest that utilizing innovations reduces operational costs, enhances speed, and improves precision. Various technologies, including internet of things (IoT), artificial intelligent (AI), model visualization, deep learning, machine learning, sensor technology and cloud platforms support the functioning of DT (Elfarri et al., 2022; Wang et al., 2022; Al Musaed & Yitmen, 2023). Several researches related to DT and these technologies have been conducted in the literature. This study aims to identify research trends by reviewing the literature on DT in the construction industry and exploring the possible applications of DT. Despite numerous studies conducted on DT so far, it is believed that a bibliometric analysis summarizing the keyword co-occurrence will provide visual data outlining the literature and comprehensive overview of research trends in the field.

Methodology

This study's primary goal is to provide information about DT knowledge as well as the latest developments within the architecture, engineering and construction sector (AEC). In order to achieve this goal, the study adopts bibliometric analysis and maps the co-occurrence of author keywords and source citations using the VOSviewer tool. Studies related to DT and the construction sector were obtained from the Scopus database. All document categories, such as conference papers, articles, reviews, book chapters, books and conference reviews were included for the purpose to reflect the researchers' views. No time restriction was used to access each source of information in the literature but the paper concentrates on research conducted in English. The advanced search engine on Scopus was selected, with the use of Title-Abstract-Keywords filtering. The following code was used for the finding: TITLE-ABS-KEY ("digital twin") AND TITLE-ABS-KEY ("construction project" OR "construction industry" OR “construction sector”) AND (LIMIT-TO (LANGUAGE, "English")). A total of 340 publications were found during the search. Afterward, the publication data from the Scopus database for the current search was exported as a CSV file for bibliometric mapping using VOSviewer software. McAllister et al. (2021) describe VOSviewer's mapping logic, where clusters consist of keywords, and their similarity is indicated by the color of their association. The size of a node is determined by the co-occurrence of the term in published papers and link strength, reflecting the intensity of keyword associations. Clusters represent groups of related keywords with common features such as subject relevance, shared research interests, and frequent occurrences in literature within the field.

Findings

In this section, the analysis of the literature and the bibliometric outcomes related to keyword co-occurrence presented, along with a discussion of the research findings. When a search was conducted in Scopus, graphs related to a total of 340 publications were accessed. Initially concerning the years of releasing, Figure 1 shows the documents by years. Scopus begins with the oldest data from the year 2018. Since 2018, there has been a considerable increase in publications, especially after 2020. The document numbers for 2022 and 2023 are quite close to one another, despite the fact that the count has been increasing annually on average until 2022. This outcome could indicate that because the number of publications reached a particular limit. Since the analysis was finished in the first few months of 2024, the statistics for that year might not fully reflect the circumstances in reality. The decline shown in the figure may not represent an actual decrease in numbers. However, we might conclude that between 2018 and 2023, interest in the DT concept expanded dramatically.

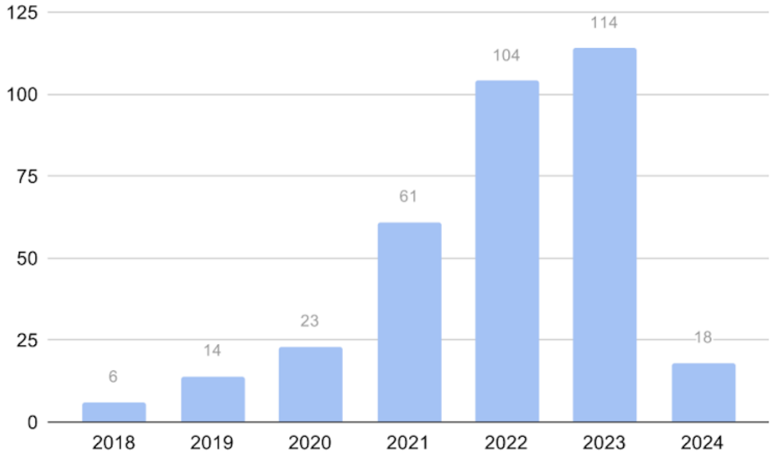

Figure 1: The total number of publications for DT in the AEC sector during 2018-2024.

Figure 2 illustrates the document type distribution. Out of the 340 papers on the topic of DT in the construction industry, articles and conference papers make up nearly 82%. Reviews (10.9%) and conference reviews (4.1%) follow with 37 and 14 publications, respectively. Books (0.9%) and book chapters (2.6%) are the least preferred types in the table.

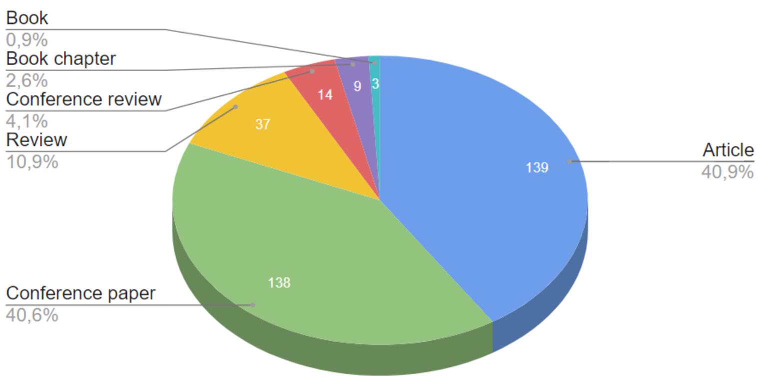

Figure 2: Type of publications.

Co-occurrence of Author Keywords

We may determine the widespread use of particular themes and the focus of research by examining the co-occurrence data of author keywords in papers. Therefore, using VOSviewer, the co-occurrence network of author keywords was created. Keyword size indicates popularity; colors differentiate clusters, and the distance indicates similarity. Additionally, links between terms indicate connections within the scope of DT and the construction industry. With 2 being the minimum number of keyword occurrences, 155 out of 868 keywords satisfy the requirement. A bibliometric map of the co-occurrence of author keywords is shown in Figure 3.

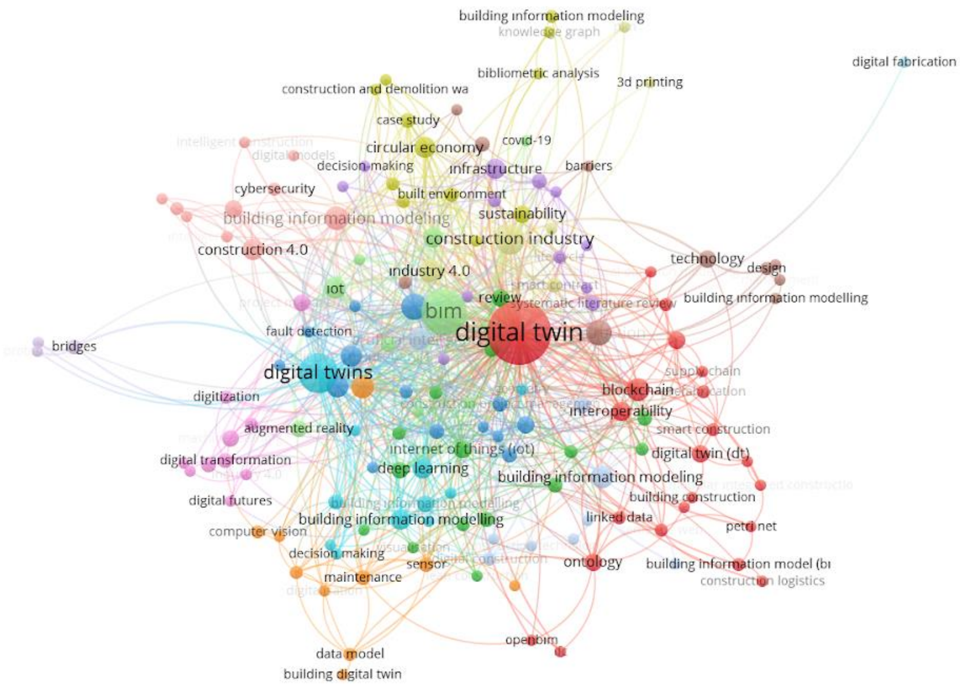

Figure 3: Bibliometric map of author keywords co-occurrence network.

According to the analysis, "digital twin" is the top keyword with 132 occurrences and in cluster 1, having a significant relationship with other relevant ideas. "BIM" is the second most common keyword, occurring 57 times, and belongs to cluster 11. The third, "digital twins," is in cluster 6 with 41 occurrences. In this map, several terms that are associated with the computer and machinery industries are found in minor clusters, including "cyber physical systems", "fault detection", "neural network", “smart contract”, “petri net” and more. This might be the case since the concept of a DT utilized in building is directly impacted by developments in the fields of computer science and technology. Additionally studies related to DT at a transitional point between various areas of expertise such as engineering, information science and computing. Smaller nodes indicate less frequent discussion in academic publications compared to larger ones. However, if it's a recent development, it may have future growth potential. The historical evolution of keywords must be examined in order to get an insight into this issue. In response to this goal, Figure 4 was generated by integrating historical data into the analysis.

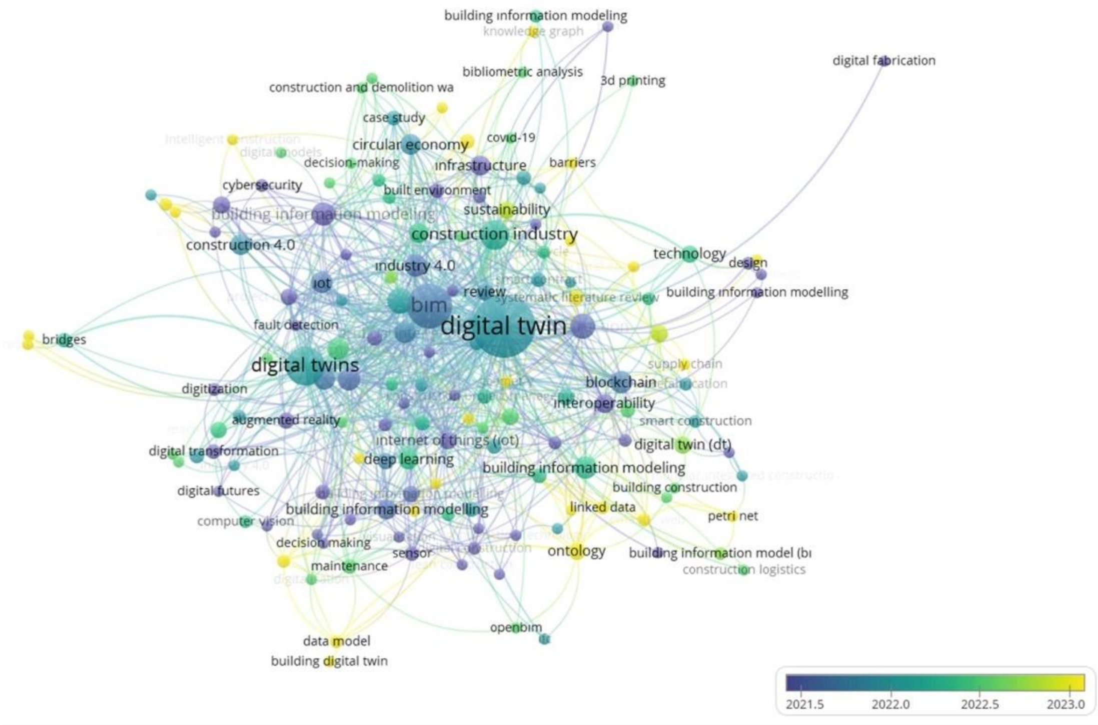

Figure 4: Bibliometric map of author keywords co-occurrence overlay.

The addition of a time option to the overlay visualization map causes the colors to change, but the screen, point size and clusters stay the same (McAllister et al., 2021). The cluster colors change from blue to yellow as the years get closer to today. In the publishing keywords displayed as an overlay by year , the terms "digital twin", "BIM", "construction industry", "internet of things" and "industry 4.0" are central to the area and frequently appear in the academic literature, representing the largest clusters. Additionally, they are seen either in the color of green or blue since researchers have used them for a longer period of time. The largest ones in the blue clusters are “BIM”, “construction”, “big data”, “blockchain” and “facility management” with 57, 14, 11, 11 and 10 document appearances in each, respectively. Except the “digital twin”, “BIM” and “construction industry” terms; “internet of things”, “artificial intelligence”, “virtual reality” and “deep learning” respectively have 15, 10, 8 and 8 occurrences in the most extensive green clusters we discover. Finally, we observe that the greatest clusters within yellow ones are “predictive maintenance” (9), “sustainable construction” (6), “construction management” (6) and “ontology” (6). Additionally, there are keywords that are primarily observed within the yellow clusters, which are highly specialized in the field of DT technology such as “semantic web”, “IFC”, “intelligent construction”, “scan to BIM” and “automation”. It appears that recent studies have mostly employed the keywords in yellow clusters. This alone does not indicate that these subjects will continue to be relevant in the future. Future research may find that they increase in size, but they may also stay small. We can state that future modifications in their dimensions could occur. Moreover according to the analysis, yellow, which is currently chosen keywords, refers to more specific topics compared to terms found in other colors.

Table 1 has been created to enhance the distinction among the keywords found in the clusters shown in Figure 3. It clearly depicts the clusters, their colors and the keywords associated with each cluster in a list format. The first cluster, "DT and Construction," consists of 22 keywords. The term "digital twin" dominates with 132 occurrences and a total link strength of 331, making it the group with the most keywords. Keywords such as "Petri net", "Linked data", "OpenBIM", "Structural equation modeling" are found in this cluster, indicating expertise in the respective field. These keywords are seen in the yellow cluster in Figure 4, further demonstrating how studies have become more specialized and in-depth recently. Cluster 2, "DT & Technological Advancements" has 15 keywords, with "Internet of Things (IoT)" as the most prominent, occurring 6 times with a total link strength of 29. Words are included in the cluster such as artificial intelligence (3), building information modeling (4), mixed reality (2), and others. Cluster 3, "DT & Management" consists of 14 keywords. The term "Internet of Things" stands out with 15 occurrences and a total link strength of 56. Keywords in this cluster such as "energy management", "predictive maintenance", "simulation" and "risk management" are observed in the yellow cluster in Figure 4, providing additional evidence of the recent trend towards increased specialization and depth in research. The top 3 clusters have the most keywords, followed by clusters C4 (12), C5 (12), C6 (11), C7 (10), C8 (10), C9 (10), C11 (10), C12 (9), C13 (6), C14 (3) and C15 (1).

Table 1. Clarification of the clusters.

No	Cluster Name	Colour	Keywords	Top 3	
				Keyword	Occurences
1	DT & Construction	Red	blockchain, building construction, building information model (bim), construction logistics, cyber-physical system (cps), digital twin (dt), digital twin construction (dtc), ifc, interoperability, linked data, literature review, modular integrated construction (mic), ontology, openbim, petri net, prefabrication, semantic web, smart construction, structural equation modelling, supply chain, sustainable construction	Digital Twin Interoperability Ontology	132 7 6
2	DT & Technological advancements	Dark Green	artificial intelligent (ai), building information modeling (bim), building information modelling (bim), collaboration, construction safety, construction site, digital twins (dt), framework, industry foundation classes (ifc), internet of things (iot), lean construction, mixed reality, review, systematic literature review (slr), visulisation	Internet of things (iot) Review Construction safety	6 6 5
3	DT & Management	Dark Blue	building information model, construction management, construction project management, cyber- physical system, energy management, engineering project management, facility management, fault detection, internet of things, optimization, predictive maintanence, risk management, simulation, smart building	Internet of things Facility management Predictive maintanence	15 10 9
4	DT & Sustainability	Yellow	bibliometric analysis, building, building information modeling, built environment, case study, circular economy, consruction and demolition waste, construction sites, digitalization, knowledge graph, sustainability, waste minimization	Circular economy Sustainability Built environment	9 6 4
5	DT & Engineering	Purple	bridge, civil engineering, decision-making, digital maturity, infrastructure, inspection, life cycle, neural network, smart cities, survey, systematic literature review, wireless sensor network	Infrastructure Bridge Systematic literature review	8 4 4
6	DT & Decision making	Blue	building information modelling, building information modelling, decision making, deep learning, digital twins, geometry, internet of things, occupational health and safety, safety management, scan-to-bim, scan-vs-bim	Digital twins Deep learnin Building information modelling	41 8 8

7	DT & Big data	Orange	3d reconstruction, big data, building digital twin, computer vision, data model, digitalisation, maintenance, modeling, sensor, structural health monitoring	Big data Maintenance Sensor	11 4 4
8	DT & Automation	Brown	automation, barriers, building information modelling (bım), construction, construction ındustry, construction sector, design, ınformation systems, management, technology	Construction Technology Construction ındustry	14 6 4
9	DT & Digitalization	Pink	aı, digital futures, digital transformation, digitization, energy efficiency, green buildings, industry 4.0, machine learning, productivity, project management	Project management Machine learning Digital transformation	5 5 4
10	DT & Cyber systems	Light Red	building information modeling, construction 4.0, cyber- phsical systems, cybersecurity, digital models, ıntelligent buildings, intelligent constructin, off-site construction, scientometric analysis, smart buildings	Building information modeling Construction 4.0 Cyber-phsical systems	12 9 6
11	DT & Virtual design	Green	arhitecture, augmented reality, bım, covid-19, engineering, gıs, ıot, smart city, virtual design and construction, virtual reality	Bım Virtual design and construction Iot	57 11 10
12	DT & Innovation	Light Blue	artificial intelligence, building information modeling (bım), construction technology, digital construction, digital technologies, ınnovation, modular construction, offsite construction, process mining	Building information modeling (bım) Artificial intelligence Modular construction	11 10 5
13	DT & Industry 4.0	Light Yellow	3d printing, construction industry, decentralization, ındustry 4.0, plm, smart contract	Construction industry Industry 4.0 Smart contract	21 11 4
14	DT & Prototyping	Lilac	bridges, prototyping, synthetic faır data	Bridges Prototyping Synthetic faır data	4 2 2
15	DT & Fabrication	Grey	digital fabrication	Digital fabrication	2

Table 2 presents the numerical data about the author keywords in the map. Within the table, the most frequently used top 20 keywords are clearly visible, which the map created with VOSviewer might not be very obvious and easy to distinguish. Similar or synonymous words have been included in the study to demonstrate how the words appear in different contexts and forms in research papers. The results simply indicate the research trends of DT in the construction sector. Although BIM and related topics continue to maintain their prominence in the literature, we can observe the emergence of AI and related subjects such as “IoT”, “predictive maintenance”, “deep learning” and “virtual reality” in recent research trends.

Table 2. Top Keywords in DT for the AEC sector.

No	Keywords	Occurences	Links	Total Link Strenght	Avg. Pub. Year
1	Digital twin	132	116	331	2021.96
2	BIM	57	68	152	2021.72
3	Digital twins	41	68	111	2022.05
4	Construction industry	21	41	69	2022.19
5	Internet of things	15	35	56	2022.07
6	Construction	14	28	45	2021.57
7	Building information modeling	12	26	35	2021.25
8	Big data	11	33	49	2021.64
9	Blockchain	11	24	43	2021.73

10	Industry 4.0	11	22	42	2021.64
11	Building information modeling (BIM)	11	17	22	2022.27
12	IoT	10	21	38	2021.70
13	Artificial intelligence	10	22	34	2021.80
14	Facility management	10	19	31	2021.70
15	Construction 4.0	9	17	25	2021.89
16	Predictive Maintenance	9	14	24	2022.44
17	Circular economy	9	18	22	2021.89
18	Building information modelling	8	24	29	2021.62
19	Deep learning	8	22	27	2022.38
20	Virtual reality	8	15	24	2022.38

Conclusion

The primary objective of this study was using bibliometric analysis to bring together the most recent research trends on DT in the AEC sector. The science mapping for DT in the construction industry was generated using the VOSviewer tool, with the literature obtained from the Scopus database. To illustrate research patterns, the article presents the total number of publications over time, together with their types, co-occurrence map of author keywords and the top 20 keywords in DT on construction sector. Popular literature keywords were grouped into clusters and labeled. To better reflect the construction sector's application area, these 15 clusters were titled in relation to DT. The analysis explored the potential of DT through research paper keywords. It can be inferred that some terms are related to notable issues in the construction sector. For instance, "openBIM", "linked data", "semantic web" and "industry foundation classes (IFC)" are remarkable for their connection to interoperability in the construction industry. Terms such as “blockchain” and “big data” could be observed in discussions related to cybersecurity of construction and privacy, while keywords like “fault detection”, “predictive maintenance” and “deep learning” may be noticeable within the context of operational cost of construction. As mentioned in the literature, achieving data interoperability, ensuring cybersecurity and managing operational costs create significant challenges in the AEC industry for DT. In the construction sector, these keywords may play different roles at different stages of the building life cycle. Terms like “BIM”" and “risk management” might be mostly notable in the design phase, while “cyber-physical systems” and “facility management” can take center stage in operation and maintenance. “IoT”, “sensors”, “smart contracts”, “optimization” and “simulation” could impact the construction phase and “circular economy” and “waste minimization” are expected to be influential in the end-of-life phase. The mentioned terms can be regarded as the latest keywords in the analysis. Thus, it is demonstrated that recently preferred terms reflect a deep expertise in construction-related topics. Considering all this information, the examined keywords may have diverse effects in the construction sector. However, it's essential to recognize the significance of these keywords and their ability to influence the future direction of the AEC industry. Numerous studies conducted in the field of DT in construction, have rapidly introduced new terms into the literature. The advancements in AI and information technology may further accelerate the emergence of new concepts in the AEC sector.

References

Almatared, M., Liu, H., Tang, S., Sulaiman, M., Lei, Z., & Li, H. X. (2022). Digital twin in the architecture, engineering, and construction industry: a bibliometric review. *Proceedings of Construction Research Congress*, pp. 670-678.

Almusaed, A., & Yitmen, I. (2023). Architectural reply for smart building design concepts based on artificial intelligence simulation models and digital twins. *Sustainability*, *15*(6), 4955.

Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y. (2020). Towards a semantic construction digital twin: directions for future research. *Automation in Construction*, *114*, 103179.

Elfarri, E. M., Rasheed, A., & San, O. (2023). Artificial intelligence-driven digital twin of a modern house demonstrated in virtual reality. *IEEE Access*.

Fuller, A., Fan, Z., Day, C., & Barlow, C. (2020). Digital twin: enabling technologies, challenges and open research. *IEEE Access*, *8*, 108952-108971.

Khajavi, S. H., Motlagh, N. H., Jaribion, A., Werner, L. C., & Holmström, J. (2019). Digital twin: vision, benefits, boundaries, and creation for buildings. *IEEE Access*, *7*, 147406-147419.

Kim, J., & Ham, Y. (2022). Real-time participatory sensing-driven computational framework toward digital twin city modeling. *Proceedings of Construction Research Congress*, pp. 281-289.

Liu, Y., Chen, K., Ma, L., Tang, S., & Tan, T. (2021). Transforming data into decision making: a spotlight review of construction digital twin. *Proceedings of ICCREM*, pp. 289-296.

Lu, Q., Parlikad, A. K., Woodall, P., Don Ranasinghe, G., Xie, X., Liang, Z., & Schooling, J. (2020). Developing a digital twin at building and city levels: case study of West Cambridge campus. *Journal of Management in Engineering*, *36*(3), 05020004.

McAllister, J. T., Lennertz, L., & Atencio Mojica, Z. (2022). Mapping a discipline: a guide to using VOSviewer for bibliometric and visual analysis. *Science & Technology Libraries*, *41*(3), 319-348.

Pan, Y., & Zhang, L. (2021). A BIM-data mining integrated digital twin framework for advanced project management. *Automation in Construction*, *124*, 103564.

Rasheed, A., San, O., & Kvamsdal, T. (2020). Digital twin: values, challenges and enablers from a modeling perspective. *IEEE Access*, *8*, 21980-22012.

Sacks, R., Brilakis, I., Pikas, E., Xie, H. S., & Girolami, M. (2020). Construction with digital twin information systems. *Data-Centric Engineering*, *1*, e14.

Si, J., Wan, C., Hou, L., Qu, Y., Lu, Y., Chen, T., & Yang, K. (2023). Self-organizing optimization of construction project management based on building information modeling and digital technology. *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, *47*(6), 4135-4143.

Sun, Y., Rameezdeen, R., Chow, C., & Gao, J. (2022). Integrating BIM and IoT for digital twin platform in building operation management: opportunities and challenges. *Proceedings of ICCREM*, pp. 284-292.

Teizer, J., Johansen, K. W., & Schultz, C. (2022). The concept of digital twin for construction safety. *Proceedings of Construction Research Congress*, pp. 1156-1165.

Wang, W., Guo, H., Li, X., Tang, S., Xia, J., & Lv, Z. (2022). Deep learning for assessment of environmental satisfaction using BIM big data in energy efficient building digital twins. *Sustainable Energy Technologies and Assessments*, *50*, 101897.

Wang, X., Liang, C. J., Menassa, C. C., & Kamat, V. R. (2021). Interactive and immersive process-level digital twin for collaborative human–robot construction work. *Journal of Computing in Civil Engineering*, *35*(6), 04021023.

Zhang, J., Cheng, J. C., Chen, W., & Chen, K. (2022). Digital twins for construction sites: concepts, LoD definition, and applications. *Journal of Management in Engineering*, *38*(2), 04021094.

Using Machine Learning Algorithms for Interpretable Predictions of House Prices and Variable Features

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Abstract

The prediction of housing prices varies depending on various dynamics, including standard and local indices. Precisely defining these factors reduces uncertainties, saving time and costs, enhancing industry decision-making model accuracy, and informing real estate policies. In this context, this study aims to develop a nearly precise housing price prediction model in three stages. Firstly, by examining the fundamental factors influencing housing prices, the best algorithm models were determined using 13 machine learning (ML) algorithms with applied hyperparameters. Compared to other ML algorithms, CatBoost and LightGBM achieved success rates of 90.8% and 89.4%, respectively. In the second stage, Bayesian hyperparameter optimization enhanced these models' accuracy. Though exhibiting specific differences in predictions, these models significantly contribute to the target model's output. The optimized hybrid model excelled in minimizing errors, achieving RMSE, R2, MAE, and MAPE values, of 0.11, 0.92, 0.08, and 0.66, respectively. Finally, the interpretation of models using SHAP and feature importance, alongside these algorithms, suggests that construction quality, area, and garage availability predominantly impact housing prices, while neighborhood and location minimally influence predictions. This study focuses on understanding the key features affecting housing prices clearly and developing a precise prediction model by interpreting these features accurately. Its results provide a correct prediction model that can improve decision-making processes for stakeholders, investors, and local governments or policymakers in the housing sector.

Keywords: *Bayesian, house price, hybrid, machine learning, quality.*

Introduction

The development of the real estate market can significantly influence the economic activities of a country, and even the entire world (Rodrigues & Lourenço, 2015). For example, the mortgage crisis in the United States led to a global financial crisis (Fligstein & Habinek, 2014), causing significant asset losses in financial markets and institutions, and slowing down economic growth worldwide (Hodson & Quaglia, 2009). Events such as global warming, climate change, and natural disasters also have a significant impact on housing prices (Nicholls, 2019; Phong & Duc Tinh, 2010; Sussman et al., 2014). During the Covid-19 pandemic, real estate prices experienced a short and temporary decline between 2019 and 2021 (Allen-Coghlan & McQuinn, 2021; Mora-Garcia et al., 2022); however, a 1% increase in earthquake risk percentage in a neighborhood has a significant impact on housing prices (Cheung et al., 2018;

Keskin, 2008; Singh, 2019). Because the housing market is a critical element for regional and national economies (Phan, 2018), house prices and their determinants are important for a wide range of stakeholders, including tenants, house owners, the real estate sector, data analysts, economic experts, and local governments (Muellbauer & Murphy, 2008). In particular, 92% of intercity price differences are attributed to local factors (Glaeser et al., 2014).

The Hedonic Price Model (HPM) is an economic tool where the characteristics that determine and influence the price of a good or service are analyzed (Oladunni & Sharma, 2016). Although the HPM is commonly used to estimate the fundamental value of a house (Hussain et al., 2019; Jafari et al., 2017; Jafari et al., 2019), typically has lower prediction accuracy compared to ML approaches (Rico-Juan & Taltavull, 2021; Kim et al., 2020). ML algorithm prediction methods significantly determine the value of a property for decision-makers (Adetunji et al., 2022; Barreca et al., 2018; Chen et al., 2021; Halket et al., 2020; H. Kim et al., 2020; Ho et al., 2021; McGreala & Taltavull, 2012; Mou et al., 2017; Noh & Park, 2021; Sahu & Singh, 2021; Soltani et al., 2022; Xue et al., 2020), focusing on the factors that influence housing prices is important (Hoxha & Salaj, 2014; Keskin, 2008). Capturing and sharing mechanisms of value can globally support governments and organizations in financing infrastructure development while alleviating financial constraints (Diao & Ferreira, 2010; Yağmur et al., 2023). However, it is necessary for governments to formulate policies promptly to sustain recovery (Park & Bae, 2015). The Housing Price Index (HPI) is used to predict inconsistencies in housing prices (Yang et al., 2020). The housing market in the United States adheres to the Standard & Poor's Case-Shiller index and the Federal Housing Finance Agency (FHFA) index (Calhoun, 1996; Park & Bae, 2015). These indices necessitate examining the relationship between housing prices and attributes, identifying necessary factors, and processing data (Abdul-Rahman et al., 2021). Accordingly, creating a robust and accurate prediction model requires identifying the factors or attributes that influence housing prices in that region or city (Rafiei & Adeli, 2016). According to Zulkifley et al. (2020), housing price predictions can be segmented based on factors such as physical characteristics (Liu & Song, 2019; Wang et al., 2015), location (Kim et al., 2021; Wen et al., 2018), and neighborhood (Wang et al., 2022; Tsao & Lu, 2022) characteristics. In addition to these three categories, broader macroeconomic factors such as the economy, inflation, stock market indices, demographic structure, and supply-demand dynamics in the real estate market also have a significant impact (Hoxha & Salaj, 2014; Lee et al., 2021; Levantesi & Piscopo, 2020; Mao et al., 2022). Among these are household income, expected return on housing investment, housing loan interest rates, demographic factors, and labor market factors (Hoxha & Salaj, 2014). Many studies show that hybrid ML models are more successful than other ML models in addressing the complexity of these factors (Azadeh et al., 2012; Mao et al., 2022; Sibindi et al., 2023; Tekin & Ucal Sarı, 2022; Kim et al., 2020).

In this study, a machine learning-based ensemble learning hybrid model (CatBoost and LightGBM) was developed to identify various factors influencing housing prices and to create the best housing price model that facilitates the analysis of the relationship between these factors. The developed hybrid model aims to play a significant role in predicting future housing prices and determining real estate policies by optimizing the base learners through the Bayesian hyperparameter optimization method, exhibiting better performance with less error compared to individual models. This study aims to identify various factors affecting housing prices and to create the best housing price model to facilitate the analysis of the relationship between these factors. In this regard, a machine learning-based ensemble learning model was developed to reduce variance and prevent overfitting, aiming to increase accuracy. This hybrid model includes CatBoost and LightGBM algorithms, with base learners adjusted using Bayesian hyperparameter optimization. It aims to play a significant role in predicting future housing prices and determining real estate policies by demonstrating better performance with less error compared to individual models. This model aims to assist consumers in coping with uncertainty and making better decisions by providing higher prediction accuracy for businesses and policymakers. In this context, the study provides a more detailed analysis of the relative effects of factors (physical, location, and neighborhood characteristics) on housing prices in a specific region. The results showed that the primary determinant of housing transaction prices in the United States is construction quality, followed by lot size, garage availability, and usable space. The study indicated that neighborhood (such as distance to open spaces and business centers) and location characteristics have a less significant impact on housing prices compared to housing units and physical features.

The study is divided into five stages: Literature Review (2), Methodology (3), Results and Discussion (4), and Conclusion (5).

Literature Review

Ensemble methods are an effective tool for improving the performance of different models (Breiman, 2001). These algorithms become ideal for our current study due to their ability to handle various data types, non-linear relationships, and high-dimensional data. Ensemble models are a widely used approach in the field of ML (Zhang et al., 2022). Sibindi et al. (2023) confirmed that the proposed hybrid LightGBM and XGBoost model provided the best prediction performance compared to baseline methods such as Adaboost, GBM, LightGBM, and XGBoost. Azadeh et al. (2012) propose a solution for predicting housing market fluctuations in Iran using a hybrid algorithm of fuzzy linear regression and fuzzy cognitive map as a decision support system, given the uncertainty and noise in the housing market. Tekin and Ucal Sarı (2022) investigated that using hybrid techniques can improve the accuracy of predictions regarding property listing prices using real market data obtained from 30,000 observations in Istanbul. Phan (2018) demonstrated that an ensemble of Stepwise and adjusted SVM outperformed other models in predicting the prices of historical houses in Melbourne, Australia. Mao et al. (2022) developed a hybrid model that ensembles different ML algorithms such as XGBoost, LightGBM, MLP, SVR, and MLR to improve prediction accuracy and stability. Kim et al. (2021) examined that by creating ML models with real transaction data in Korea, the hybrid model they developed can improve prediction accuracy in housing price predictions by using different algorithm ensembles. In this way, when a high-priority prediction model is created, highly accurate predictions are obtained. This means that organizations involved in housing finance can access more precise valuation results, accurate financial solutions, and lower capital costs.

In this study, a hybrid model has been constructed using the CtaBoost and LightGBM algorithms. Both CatBoost and LightGBM utilize a leaf-wise tree structure in their algorithms. Tree-based algorithms offer many advantages, such as interpretability, reduced data preparation requirements, versatility, and management of complex relationships (Zhang et al., 2015). Decision trees help us understand relationships between different entities by interpreting them simply (Miao et al., 2004), providing easier understanding compared to other techniques (Kotsiantis, 2013). This tree structure creates a complex and branching framework, providing the highest information gain for faster training on large datasets (Yang et al., 2015). Additionally, CatBoost and LightGBM serve as powerful Gradient Boosted Decision Tree (GBDT) tools for tasks like classification and regression in large-scale data scenarios (Shi et al., 2018). GBDT outperforms other ML algorithms in heterogeneous data tasks

(Prokhorenkova et al., 2018). However, GBDT is not as effective as neural networks in homogeneous data tasks (Johnson & Khoshgoftaar, 2019). Accordingly, it is important to choose the right ML algorithm considering the data type. CatBoost and LightGBM, along with their similarities, also have differences. CatBoost is a gradient-boosting algorithm designed to efficiently handle datasets with categorical features (Nguyen et al., 2022). The aim is to ensemble predictions from different models to achieve a stable and generalizable result, thereby preventing overfitting (Ostroumova et al., 2017). It provides better prediction accuracy and eliminates prediction drift with the sequential boosting algorithm (Huang et al., 2023). LightGBM, on the other hand, is a gradient-boosting algorithm developed to handle large, sparse, and unstructured datasets (Ma et al., 2021). In particular, it includes various features such as histogram-based one-sided sampling and special feature bundling (Friedman, 2001). LightGBM is an advanced gradient-boosting ML algorithm that offers improved accuracy, more efficient memory usage, and enhanced speed (Alshboul et al., 2022). Developing models with higher prediction accuracy is important for coping with uncertainty. In the study, applying Bayesian hyperparameter optimization to the hybrid model is important as it minimizes error and enhances the accuracy of the model.

Methodology

Data Preparation

The data used in this study was obtained from the ongoing competition USA Iowa - Ames Housing Market accessed through the Kaggle website (URL). The original dataset consists of 1460 observations and 81 features (79 explanatory features, 1 target feature, and 1 ID). Each observation represents the actual sale prices of houses in the city of Ames. Data preparation consists of two main stages: data preprocessing and feature engineering. Before using prediction models for house prices, comprehensive preprocessing of the dataset (numerical & categorical, handling missing & outlier values, correlation matrix, target feature, etc.) is crucial. The Feature Engineering stage is divided into 5 steps: (Step 1) Cleaning. Data cleaning involves identifying and processing outlier values (with thresholding: low_quantile=0.10, up_quantile =0.90). Missing values indicating the absence of certain features were filled with 'No', and for 'object' type features with 20 or fewer classes, missing values were filled with the mode, while other features were imputed with the 'mean' or 'median'. (Step 2) Transformation. Scaling techniques such as StandartScaler and MinMaxScaler were used for the balanced scaling of features. Additionally, skewness and kurtosis analyses were conducted to examine the normal distribution of each feature. Due to the wide range and numerous outlier values in the SalePrice (target/dependent feature) values, a logarithmic transformation was applied to normalize the data. (Step 3) Encoding and Feature Extraction. Rare Encoding is applied to less effective features, and new features are created based on the correlation matrix. The correlation matrix plays an important role in creating new features; numerical values are normalized, and Label Encoding and One-Hot Encoding techniques are applied to categorical values. (Step 4) Feature Iteration. Feature iteration is used after creating hyperparameter models during predictions. (Step 5) Feature Selection. Feature selection was used in the interpretability steps to evaluate the performance of the model. Furthermore, in the dataset, the distribution of Features (81) originally shows Categorical Features (53), Numerical Features (28), Categorical but Cardinal Features (0), and Numerical but Categorical Features (10). However, after applying Rare Encoding & New Features, these features increase to 101, 58, 43, 0, and 15, respectively; while after applying Binary Encoding & One-Hot Encoding, they reach the numbers 311, 268, 43, 0, 268, respectively.

Model Selection and Development

Before data modeling, the cleaned dataset was divided into a training dataset (80%) and a test dataset (20%) used for evaluating the model. Firstly, various models were included to comprehensively compare their performances and find the best-performing model (Table 1). A systematic approach, namely 5-fold cross-validation and GridSearchCV techniques, was used to optimize the hyperparameters of ML models. GridSearchCV is used to find the best hyperparameter combinations for each model, and then the models are trained with these parameters. Subsequently, the performance of the models is evaluated. However, linear algorithms may risk overfitting when the relationships between the data are not linear (Bartlett et al., 2019). The Learning Curve graphs of these models showed overfitting for Bayesian, while for MLR, they indicated underfitting, and the heterogeneous nature of the dataset led to the initial elimination of these methods (Bayesian, Ridge, Multiple Linear, ElasticNet, and Lasso Regression) (Table 1). When selecting an ML model for a specific problem or dataset, it is important to consider these limitations (Uddin et al., 2023).

Table 1. ML algorithm selection.

Algorithms	Scoring Index (SI)*
Categorical Boosting (CatBoost)	1.3074
Bayesian Regressor	1.2971
Ridge Regression	1.2533
Light Gradient Boosting Machine (LightGBM)	1.2262
Extreme Gradient Boosting (XGBoost)	1.2094
Gradient Boosting Machine (GBM)	1.1821
Multiple Linear Regression (MLR)	1.1867
Lasso Regression	1.0842
ElasticNet Regression	1.0759
Random Forest (RF)	1.0711
Adaptive Boosting (AdaBoost)	0.8277
Classification and Regression Trees (CART)	0.7026
K-Nearest Neighbors (KNN)	0.4960

* SI = R^2 * (1 / MAPE). The SI value used to measure the performance of each model is calculated by combining R2 and MAPE values, taking into account both accuracy and variance.

Subsequently, CatBoost and LightGBM, which ranked first, were selected to create the ensemble model as they are tree-based models. CatBoost and LightGBM demonstrated the best performance with higher R2 values, and lower RMSE, MSE, and MAE values, indicating smaller errors. Using Bayesian Optimization, the ensemble model for CatBoost and LightGBM was optimized. Predictions were made with the models retrained with the best hyperparameters, and ensemble predictions were formed by taking the weighted average of these predictions. Finally, the performance of the ensemble model was evaluated, and relevant metrics were determined. Additionally, SHAP analysis was used for interpreting the model and determining the effect of input features on output targets. For this purpose, an explainer named TreeExplainer was used in scikit-learn models. The analysis was performed in Python using the

Scikit-learn and matplotlib libraries for classical ML models, in addition to the PyCharm IDE for development and the ensemble hybrid model.

Performance Evaluation Metrics

Prediction error metrics were used to evaluate the performance accuracy of the proposed model. The metrics used include Root Mean Squared Error (RMSE), determination coefficient (R2), Mean Absolute Error (MAE), and Mean Absolute Percentage Error (MAPE). The equations used for the evaluation metrics are as follows:

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \tag{1}$$

$$r^2 = 1 - \frac{\sum_{i=1}^{n}(\hat{y}_i - \bar{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \tag{2}$$

$$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i| \tag{3}$$

$$\text{MAPE} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{y_i - \hat{y}_i}{y_i}\right| \times 100 \tag{4}$$

with n being observations, y_i as actual values, $\hat{y}_i$ as predicted values, and $\bar{y}$ is the mean target value of all test samples.

Model Evaluation Results and Discussion

Performance Evaluation of the Hybrid Model

In 200 trials, the best hyperparameter combinations were found for the CatBoost and LightGBM models. The CatBoost model achieved the lowest RMSE as the objective function value in the 196th trial, while the LightGBM model achieved the lowest RMSE in the 149th trial. The CatBoost model achieved a better objective value of 0.121 RMSE compared to the LightGBM model. The hybrid model showed better performance in optimizing the objective function to improve performance. The RMSE of the hybrid model decreased from 0.1224 with default hyperparameters to 0.1145 with Bayesian hyperparameter combination. This indicates that the hybrid model is the best model for predicting house prices with reduced variance and increased accuracy. However, the Bayesian method, which eliminates uncertainty, yields results faster than GridSearchCV used in base learners, its computation time is higher due to Bayesian hyperparameter processing and the size of the dataset.

Table 2. Performance evaluation of the hybrid CatBoost and LightGBM.

Model	RMSE↓	R2↑	MAE↓	MAPE↓
CatBoost-LightGBM without Bayesian	0.1224	0.9063	0.0847	0.7105
CatBoost-LightGBM with Bayesian	0.1145	0.9181	0.0791	0.6632

Interpretation of the Hybrid CatBoost - LightGBM Model

In the developed hybrid model, Shapley Additive Explanation (SHAP) plots were used to interpret the predictions accurately (Abdel-Razek et al., 2022; Wang et al., 2023). The SHAP concept was created to assess the importance of an individual player within a team (Shapley, 1953). The SHAP plot provides a detailed view of the impact of each feature on predictions, in addition to ranking the features (Lundberg & Lee, 2017) and quantitatively specifying the feature's impact on the output (Mangalathu et al., 2020). A high SHAP value for a feature indicates that it significantly impacts the model output (Lee et al., 2023); positive and negative values reflect whether the feature increases or decreases the output (Mao et al., 2022).

In this study, it has been observed that the contributions of the CatBoost and LightGBM models to the hybrid model are almost equal. The contribution percentages of the two models to the hybrid model are 50.41% and 49.59%, respectively. There is a 0.82% difference between the base learners. The nearly equal contributions of the two algorithms to the prediction model have enhanced the success of the hybrid model. In terms of features, the impact of features has been evaluated based on the mean absolute SHAP values by ranking the effects of the predicted features on housing sale prices, as seen in Figure 1.

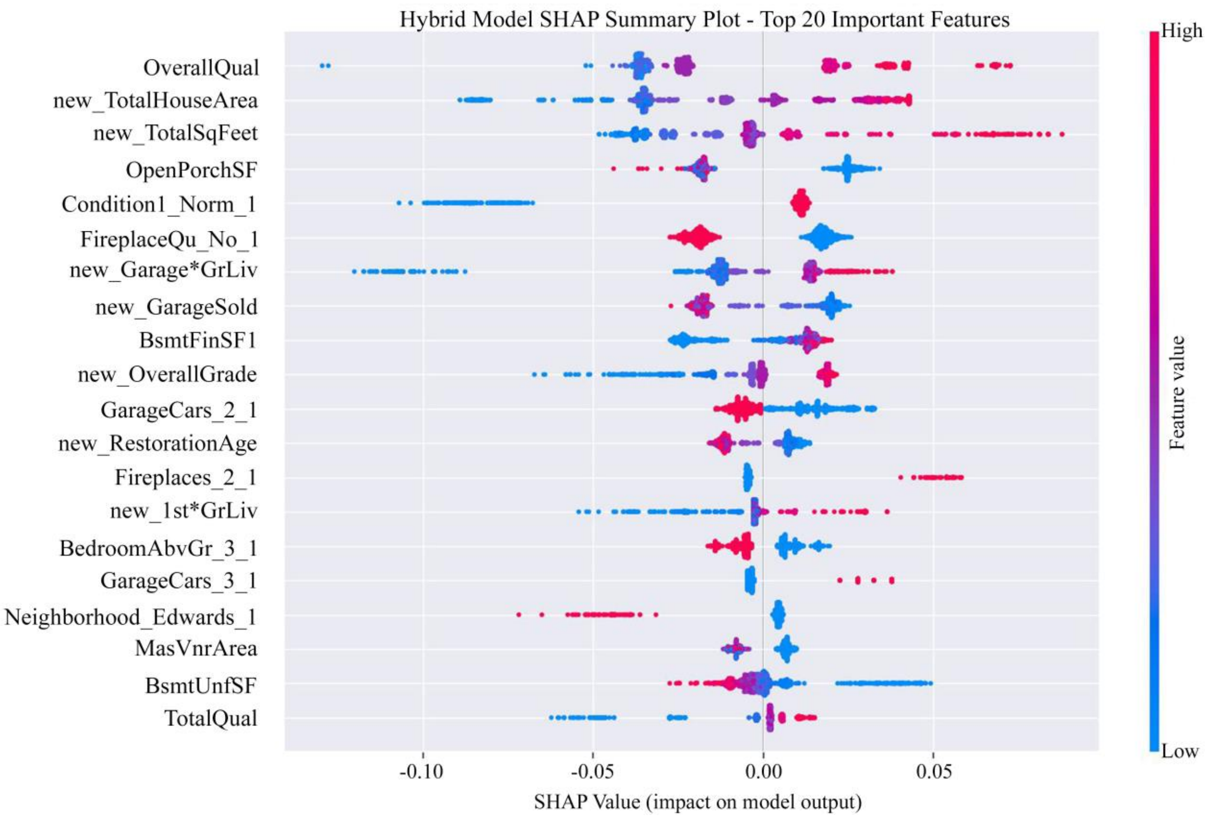

Figure 1: SHAP summary chart of the distribution and impact of the features in predicting house prices with the Hybrid Model.

Figure 1 shows the features that contribute the most to the hybrid model's prediction. These features are presented in the top 20 SHAP summary charts and are derived from the ensemble of the CatBoost and LightGBM algorithms. The features that most significantly influence the predictions of the hybrid model are as follows: house quality (OverallQual, new_OverallGrade, FireplaceQu, MasVnrArea, TotalQual), total house area (new_TotalHouseArea), usable house area (new_TotalSqFeet), porch, living area and circulation (OpenPorchSF, new_GarageGrLiv, new_1stGrLiv, and BsmtUnfSF), access to transportation facilities (Condition1), year of restoration (new_RestorationAge), duration of the garage and 2 to 3 car garages (new_GarageSold, GarageCars_2, GarageCars_3), three bedrooms above ground (BedroomAbvGr_3_1), presence of 2 fireplaces (Fireplace_2_1), and the neighborhood (Neighborhood_Edwards).

Figure 2 shows the importance of different features, but it does not determine the relationship of the feature with the outputs. Therefore, the SHAP summary chart (Figure 1) is used to demonstrate how each feature is related to the outputs.

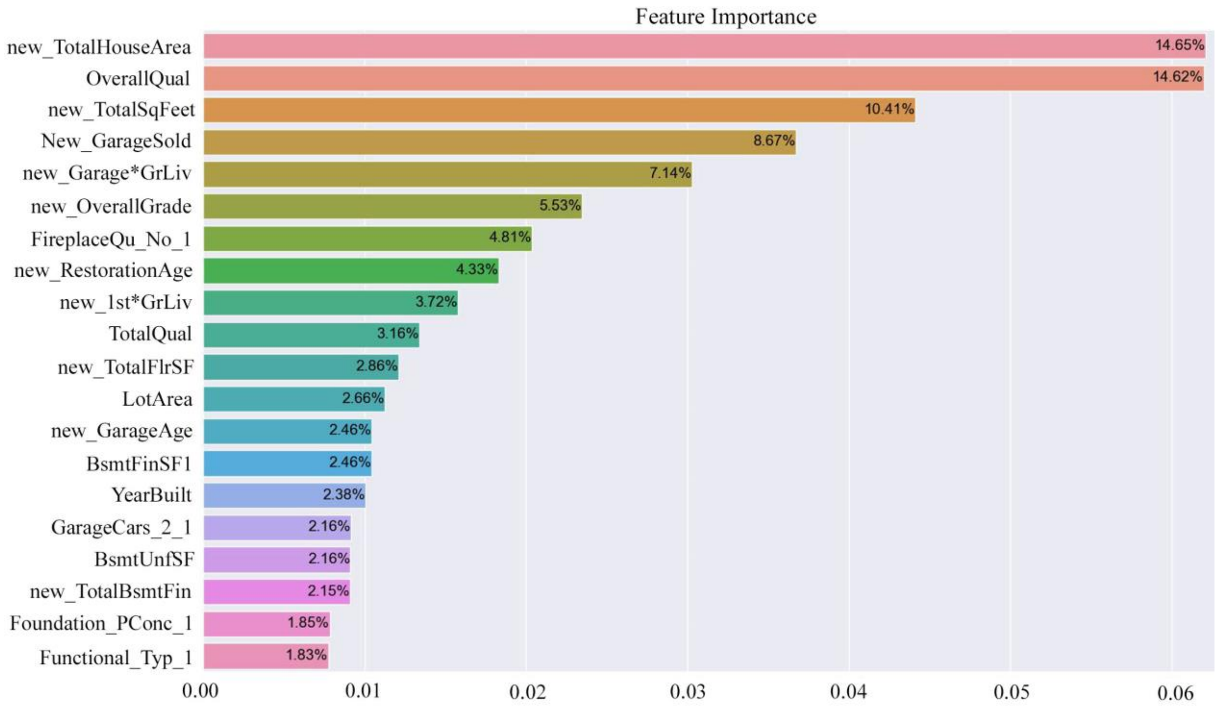

Figure 2: Hybrid model feature importance summary.

Figure 2 shows the degree of importance of the features; these outputs help us understand the effects of the model on house prices. In the figure, the first five features account for more than 50% of the model's effect, while the first eleven features reflect 80%. This situation, while also providing Pareto analysis, ensures the efficient management and optimal utilization of resources in both economic and quality management contexts. Furthermore, these data can be taken into consideration when making an important assessment for a homebuyer or homeowner. It is possible to note that factors such as the construction quality of the house, total area, usable space, garage size, and garage quality have a significant impact on the price and greatly influence it.

Discussion

This study developed a hybrid model by an ensemble of the CatBoost and LightGBM algorithms to create the best house price prediction model. This hybrid model achieved the most accurate results through the optimization of hyperparameters using Bayesian optimization. Bayesian hyperparameter optimization was applied to the base learners to determine the best set of hyperparameters (Table 3).

Table 3. Optimal hyperparameter values for the base learners and hybrid models.

Algorithm category	Name	Hyperparameter
Base learner	CatBoost (best parameters)	bagging_temperature = 0.5, depth = 5, iterations = 200, l2_leaf_reg =1, learning_rate = 0.1
	LightGBM (best parameters)	learning_rate=0.1, max_depth=3, min_child_samples =20, n_estimators=200, num_leaves=20
Optimization	Bayesian (CatBoost + LightGBM)	iterations_catboost = (50, 200), learning_rate_catboost = (0.01, 1.0), depth_catboost = (3, 7), l2_leaf_reg_catboost = (1, 5), bagging_temperature_catboost = (0.5, 1.5), max_depth_lgb = (3, 7), learning_rate_lgb = (0.01, 0.5), num_leaves_lgb = (20, 40), n_estimators_lgb= (50, 200), min_child_samples_lgb = (10, 30)
Hybrid	CatBoost + LightGBM (best parameters)	bagging_temperature_catboost=0.796, depth_catboost=4, iterations_catboost=196, l2_leaf_reg_catboost=4, learning_rate_catboost=0.175, learning_rate_lgb=0.085, max_depth_lgb=3, min_child_samples_lgb=18, n_estimators_lgb= 149, num_leaves_lgb=38

However, the study has some limitations. Initially, hyperparameters were tested across various iterations within the range of 50 to 500. Yet, the optimization process was limited to a maximum of 200 trials due to the discovery of the optimal hyperparameter set before 200 iterations and the extensive runtime of the program over a wide range. Hyperparameter optimization requires significant computational resources and time. To enhance efficiency, specific hyperparameters are selected for each study (Table 3). These include terms like 'n_estimators' for determining the number of trees, 'iteration' for specifying the number of repetitions, 'depth' and 'max_depth' for establishing the maximum depth of decision trees, 'bagging temperature' for controlling the sampling process of trees, 'num_leaves' for setting the maximum number of leaves, 'l2_leaf_reg' for L2 regularization, and 'min_child_samples' for deciding the minimum number of samples required to split a tree. However, the parameter ranges could not be taken too wide due to computational power or time constraints. On the other hand, adjusting hyperparameters with wide ranges or having a large number of parameters can increase the computational burden and reduce efficiency in model training. The parameters used were employed to control the complexity of the model and prevent overfitting in the hybrid model, addressing issues encountered in traditional ML algorithms. When they have higher values, the model becomes more complex, while lower values lead to simpler and more generalizable models. This can provide less diversity and more stability but increases the risk of overfitting. Thus, setting them too high can lead to overfitting, while setting them too low can lead to underfitting. In this case, each parameter affects the model's ability to solve a specific problem and therefore should be carefully selected. Additionally, not considering the contribution of each hyperparameter to the model's performance is another limitation, as a comprehensive analysis of the hyperparameter tuning process in LightGBM and CatBoost has not been conducted. Therefore, selecting the correct parameters is highly important. Hyperparameter parallel coordinate analysis provides a good solution for understanding the interaction between hyperparameters and how to make optimal adjustments to achieve the best performance. However, due to computational constraints, in this study, hyperparameters were optimized using GridSearchCV and cross-validation techniques, yielding a solution by selecting parameters that yield the best performance within the specified range.

Additionally, the primary objective of this study is to identify factors influencing housing prices and to develop a housing price model that facilitates the analysis of this relationship. The study examines physical attributes, location, and neighborhood characteristics that influence housing prices. However, deeper analyses are needed to understand the effectiveness of specific factors in a particular region or type of housing. Housing prices are influenced not only by these attributes but also by economic factors (such as economic conditions, inflation, stock market indices, etc.) and even demographic structures, as well as real estate market dynamics related to supply and demand. The absence of these features from the model is another limitation of the study, and considering these factors is important for a more comprehensive analysis.

Finally, in the study, new features were obtained by selecting subsets of original features using the feature extraction method and creating combinations of these subsets, while also employing correlation matrix and feature importance metrics for feature selection. When examining the features in the model, it is observed that these features, which begin with "new_" (those generated through feature extraction), make significant contributions to the model prediction. However, alongside these features that provide a high contribution, it has been observed that some features contribute very minimal or not at all to the model prediction according to SHAP analysis. Among these features, the following have minimal to no contribution to the model prediction or provide a few contributions: neighborhood (except Neighborhood_Edwards), location (except for accessibility to transportation facilities and proximity to main road or railway - Condition1_Norm), housing characteristics (housing style, roof type, roof material, exterior covering, and exterior covering material quality), basement (basement height, overall basement condition, basement exposure/walkout, basement finished area quality), heating and electrical systems, interior features of the garage, and pool area. However, these features were not eliminated from the model, nor was an investigation conducted into how model predictions would be affected if they were eliminated. Principal Component Analysis (PCA) could be used to reduce the dimensionality of the dataset by combining features that contribute minimally or not at all to the prediction model. Subsequently, after PCA, these features could be eliminated by examining the coefficients and variances of the resulting principal components. Thus, the model could be simplified, diminishing the impact of complexity and insignificant features. Based on the results of PCA, combining the least effective or non-influential features could lead to the creation of new features during the feature engineering stage, thereby further enhancing the model's performance. Particularly, principal components with higher variance in PCA are generally considered more significant and contain more information (Timmerman, 2003). Therefore, utilizing PCA as interpretable features may enhance the accuracy of housing predictions and contribute to model development.

Conclusion

This study highlights the importance of housing prediction and features, demonstrating the significant role of data-driven methods in performance evaluation. The optimized hybrid CatBoost and LightGBM model outperforms individual base ML algorithms with lower RMSE, MAE, and MAPE, as well as better R2 performance results. Furthermore, it has been observed that the ensemble model created with Bayesian hyperparameters exhibits better performance. However, the processing time of the hybrid model is higher due to handling hyperparameters for base learners and obtaining predictions, particularly considering the size of the dataset. It is crucial to note that Bayesian hyperparameter optimization enhances the accuracy of the model and prevents overfitting. Therefore, hyperparameter tuning should be performed for better performance of the base learners, and comparisons should be made by applying different hyperparameter optimization techniques. In the study, the features that have the most significant impact on the predictions of the hybrid model are quality, area, porch, living area, circulation, restoration, and garage features. However, it has been observed that certain features such as neighborhood, location, decoration, heating and electrical systems, and pool area contribute very minimal or nearly none to the model predictions. This research focuses on achieving a clear understanding of the fundamental features influencing housing prices and developing a precise prediction model by interpreting these features accurately. The research findings provide a prediction model of sufficient accuracy that can help reduce uncertainties in the housing market, enabling stakeholders, investors, and policymakers to improve their decision-making processes with more informed choices. Furthermore, for further research, different datasets from various regions and countries should be utilized, and the model's performance should be evaluated in terms of accuracy and time complexity.

References

Abdel-Razek, S., Marie, H., Alshehri, A., & Elzeki, O. (2022). Energy efficiency through the implementation of an AI model to predict room occupancy based on thermal comfort parameters. *Sustainability, 14,* 7734.

Abdul-Rahman, S., Mutalib, S., Zulkifley, N., & Ibrahim, I. (2021). Advanced machine learning algorithms for house price prediction: case study in Kuala Lumpur. *International Journal of Advanced Computer Science and Applications, 12,* 12.

Adetunji, A., Akande, O., Ajala, F., & Oyewo, O. (2022). House price prediction using random forest machine learning technique. *Procedia Computer Science, 199,* 806-813.

Allen-Coghlan, M., & McQuinn, K. M. (2021). The potential impact of Covid-19 on the Irish housing sector. *International Journal of Housing Markets and Analysis, 14,* 636-651.

Alshboul, O., Shehadeh, A., Al Mamlook, R. E., Almasabha, G., Almuflih, A. S., & Alghamdi, S. Y. (2022). Prediction liquidated damages via ensemble machine learning model: towards sustainable highway construction projects. *Sustainability, 14,* 9303.

Azadeh, A., Ziaei, B., & Moghaddam, M. (2012). A hybrid fuzzy regression-fuzzy cognitive map algorithm for forecasting and optimization of housing market fluctuation. *Expert Systems with Applications, 39,* 298-315.

Bartlett, P.L., Long, P. M., Lugosi, G., & Tsigler, A. (2019). Benign overfitting in linear regression. *Proceedings of the National Academy of Sciences of the United States of America (PNAS), 117*(48) 30063-30070.

Barreca, A., Curto, R., & Rolando, D. (2018). Housing vulnerability and property prices: spatial analyses in the Turin real estate market. *Sustainability, 10,* 3068.

Breiman, L. (2001). Random forests. *Mach Learning, 45*(1), 5-32.

Calhoun, C. (1996). *OFHEO house price indexes: HPI technical description*. http://www.ofheo.gov/Media/Archive/house/hpi_tech.pdf

Chen, H., Voigt, S., & Fu, X. (2021). Data-driven analysis on inter-city commuting decisions in Germany. *Sustainability, 13,* 6320.

Cheung, R., Wetherell, D., & Whitaker, S. (2018). Induced earthquakes and housing markets: evidence from Oklahoma. *Regional Science and Urban Economics, 69,* 153-166.

Diao, M., & Ferreira, J. (2010). Residential property values and the built environment: empirical study in Boston, Massachusetts, Metropolitan Area. *Transportation Research Record*, *2174*(1) 138-147.

Fligstein, N., & Habinek, J. (2014). Sucker punched by the invisible hand: the world financial markets and the globalization of the US mortgage crisis. *Socio-Economic Review*, *12*(4), 637-665.

Friedman, J. H. (2001). Greedy function approximation: a gradient boosting machine. *Annual Statistics*, *29,* 1189-1232.

Glaeser, E., Gyourko, J., Morales, E., & Nathanson, C. (2014). Housing dynamics: an urban approach. *Journal of Urban Economics, 81,* 45-56.

Halket, J., Nesheim, L., & Oswald, F. (2020). The housing stock, housing prices, and user costs: the roles of location, structure, and unobserved quality. *International Economic Review, 61,* 4.

Hancock, J. T., & Khoshgoftaar, T. M. (2020). CatBoost for big data: an interdisciplinary review. *Journal of Big Data, 7,* 94.

Ho, W., Tang, B., & Wong, S. (2021). Predicting property prices with machine learning algorithms. *Journal of Property Research*, *38*(1) 48-70.

Huang, P., Dai, K., & Yu, X. (2023). Machine learning approach for investigating compressive strength of self-compacting concrete containing supplementary cementitious materials and recycled aggregate. *Journal of Building Engineering, 79,* 107904.

Hussain, T., Abbas, J., Wei, Z., & Nurunnabi, M. (2019). The effect of sustainable urban planning and slum disamenity on the value of neighboring residential property: application of the hedonic pricing model in rent price appraisal. *Sustainability, 11,* 1144.

Jafari, A., Valentin, V., & Berrens, R. (2017). Estimating the economic value of energy improvements in U.S. residential housing. *Journal of Construction Engineering and Management, 143,* 8.

Jafari, A., & Akhavian, R. (2019). Driving forces for the US residential housing price: a predictive analysis. *Built Environment Project and Asset Management, 9*(4) 515-529.

Johnson, J. M., & Khoshgoftaar, T. M. (2019). Medicare fraud detection using neural networks. *Journal of Big Data, 6,* 63.

Ke, G., Meng, Q., Finley, T., Wang, T., Chen, W., Ma, W., Ye, Q., & Liu, T. Y. (2017). Lightgbm: a highly efficient gradient-boosting decision tree. In: I. Guyon, U. V. Luxburg, S. Bengio, H. Wallach, R. Fergus, S. Vishwanathan, & R. Garnett (Eds.), *Advances in neural information processing systems* (pp. 3146-3154).

Kim, H., Kwon, Y., & Choi, Y. (2020). Assessing the impact of public rental housing on the housing prices in proximity: based on the regional and local level of price prediction models using long short-term memory (LSTM). *Sustainability, 12*, 7520.

Kim, Y., Choi, S., & Yi, M. (2020). Applying comparable sales method to the automated estimation of real estate prices. *Sustainability, 12*, 5679.

Kim, J., Won, J., Kim, H., & Heo, J. (2021). Machine-learning-based prediction of land prices in Seoul, South Korea. *Sustainability, 13,* 13088.

Kotsiantis, S. B. (2013). Decision trees: a recent overview. *Artificial Intelligence Review, 39*(4), 261-283.

Lee, S. H., Kim, J. H., & Huh, J. H. (2021). Land price forecasting research by macro and micro factors and real estate market utilization plan research by landscape factors: big data analysis approach. *Symmetry, 13*, 616.

Lee, Y., Oh, J., Kim, D., & Kim, G. (2023). SHAP value-based feature importance analysis for short-term load forecasting. *Journal of Electrical Engineering & Technology, 8,* 579-588.

Levantesi, S., & Piscopo, G. (2020). The importance of economic variables on London real estate market: a random forest approach. *Risks, 8,* 112.

Liu, C., & Song, W. (2019). Perspectives of socio-spatial differentiation from soaring housing prices: a case study in Nanjing, China. *Sustainability, 11*, 2627.

Lundberg, S., & Lee, S. I. (2017). A unified approach to interpreting model predictions. *Proceedings of 31st Conference on Neural Information Processing Systems*.

Ma, M., Zhao, G., He, B., Li, Q., Dong, H., Wang, S. (2021). XGBoost-based method for flash flood risk assessment. *Journal of Hydrology,* 598.

Mangalathu, S., Hwang, S. H., & Jeon, J. S. (2020). Failure mode and effects analysis of RC members based on machine-learning-based SHapley Additive exPlanations SHAP) approach. *Engineering Structures,* 219.

Mao, Y., Duan, Y., Guo, Y., Wang, X., & Gao, S. (2022). A study on the prediction of house price index in first-tier cities in China based on heterogeneous integrated learning model. *Journal of Mathematics,* 1-16.

McGreala, S., & Taltavull, P. (2012). An analysis of factors influencing accuracy in the valuation of residential properties in Spain. *Journal of Property Research Aquatic Insects, 29*(1), 1-24.

Mou, Y., He, Q., & Zhou, B. (2017). Detecting the spatially non-stationary relationships between housing price and its determinants in China: guide for housing market sustainability. *Sustainability, 9,* 1826.

Mora-Garcia, R., Cespedes-Lopez, M., & Raul Perez-Sanchez, V. (2022). Housing price prediction using machine learning algorithms in COVID-19 times. *Land, 11*, 2100.

Muellbauer, J., & Murphy, A. (2008). Housing markets and the economy: the assessment. *Oxford Review of Economic Policy, 24*(1), 1-33.

Nguyen, N. H., Tong, K. T., Lee, S. (2022). Prediction of compressive strength of cement-based mortar containing metakaolin using explainable categorical gradient boosting model. *Engineering Structures, 269,* 114768.

Nicholls, S. (2019). Impacts of environmental disturbances on housing prices: a review of the hedonic pricing literature. *Journal of Environmental Management, 246,* 1-10.

Noh, S., & Park, J. (2021). Café and restaurant under my home: predicting urban commercialization through machine learning. *Sustainability, 13,* 5699.

Oladunni, T., & Sharma, S. (2016). Hedonic housing theory – a machine learning investigation. *Proceedings of 15th IEEE International Conference on Machine Learning and Applications.*

Ostroumova, L., Gusev, G., Vorobev, A., Dorogush, A. V., & Gulin, A. (2017). CatBoost: unbiased boosting with categorical features. *Proceedings of 32nd Conference on Neural Information Processing Systems*.

Park, B., & Bae, J. (2015). Using machine learning algorithms for housing price prediction: the case of Fairfax County, Virginia housing data. *Expert Systems with Applications, 42,* 2928-2934.

Phan, T. (2018). Housing price prediction using machine learning algorithms: the case of Melbourne City, Australia*, proceedings of International Conference on Machine Learning and Data Engineering.*

Phong, T., & Duc Tinh, B. (2010). Housing sector considerations in disaster risk reduction and climate change adaptation. In R. Shaw, J. M. Pulhin, & J. Jacqueline Pereira (Eds.) *Climate change adaptation and disaster risk reduction: issues and challenges (community, environment and disaster risk management* (pp. 291-302). Emerald Group Publishing Limited.

Prokhorenkova, L., Gusev, G., Vorobev, A., Dorogush, A. V., & Gulin, A. (2018). Catboost: unbiased boosting with categorical features. In S. Bengio, H. Wallach, H. Larochelle, K. Grauman, N. Cesa-Bianchi, & R. Garnett (Eds.), *Advances in neural information processing systems* (pp. 6638-6648). Curran Associates.

Rafiei, M., & Adeli, H. (2016). A novel machine learning model for estimation of sale prices of real estate units. *Journal of Construction Engineering and Management, 142,* 2.

Rico-Juan, J., & Taltavull, P. (2021). Machine learning with explainability or spatial hedonics tools? An analysis of the asking prices in the housing market in Alicante, Spain. *Expert Systems With Applications, 171*, 114590.

Rodrigues, P. M., & Lourenço, R. F. (2015). *House prices: bubbles, exuberance, or something else? Evidence from euro area countries*. Working Papers, Lisbon, pp. 1-39.

Sahu, M., & Singh, A. (2021). Review on house price prediction using machine learning. *International Journal for Research in Applied Science & Engineering Technology, 9.*

Shapley, L. (1953). A value for N-person games: contributions to the theory of games. In H. W. Kuhn, A. W. Tucker (Eds.), *Annals of mathematical studies* (pp. 307-317). Princeton University Press.

Shi, Y., Li, J., & Li, Z. (2018). Gradient boosting with piece-wise linear regression trees. *Proceedings of the Twenty-Eighth International Joint Conference on Artificial Intelligence.*

Sibindi, R., Mwangi, R. W., & Waititu, A. G. (2023). A boosting ensemble learning-based hybrid light gradient boosting machine and extreme gradient boosting model for predicting house prices. *Engineering Reports, 5,* e12599.

Singh, R. (2019). Seismic risk and house prices: Evidence from earthquake fault zoning. *Regional Science and Urban Economics, 75,* 187-209.

Soltani, A., Heydari, M., Aghaei, F., & Pettit, C. (2022). Housing price prediction incorporating spatio-temporal dependency into machine learning algorithms. *Cities, 131,* 103941.

Sussman, F., Saha, B., Bierwagen, B. G., Weaver, C. P., Cooper, W., Morefield, P. E., & Thomas, J. V. (2014). Estimates of changes in county-level housing prices in the United States under scenarios of future climate change. *Climate Change Economics, 5*(3), 1450009.

Tekin, M., & Ucal Sarı, İ. (2022). Real estate market price prediction model of Istanbul. *Real Estate Management and Valuation, 30,* 1-16.

Timmerman, M. E. (2003). Principal component analysis. *Journal of the American Statistical Association, 98*(464), 1082-1083.

Tsao, H., & Lu, C. (2022). Assessing the impact of aviation noise on housing prices using new estimated noise value: the case of Taiwan Taoyuan International Airport. *Sustainability, 14,* 1713.

Uddin, M. N., Ye, J., Deng, B., Li, L., & Yu, K. (2023). Interpretable machine learning for predicting the strength of 3D printed fiber-reinforced concrete (3DP-FRC). *Journal of Building Engineering, 72*, 106648.

Wang, Y., Zhao, L., Sobkowiak, L., Guan, X., & Wang, S. (2015). Impact of urban landscape and environmental externalities on spatial differentiation of housing prices in Yangzhou City. *Journal of Geographical Sciences, 25*(9), 1122-1136.

Wang, J., Wu, K., & Du, Y. (2022). Does air pollution affect urban housing prices? Evidence from 285 Chinese prefecture-level cities. *Journal of Cleaner Production, 370*, 133480.

Wang, Q., Li, C., Hao, D., Xu, Y., Shi, X., Liu, T., Sun, W., Zheng, Z., Liu, J., Li, W., Liu, W., Zheng, J., & Li, F. (2023). A novel four-dimensional prediction model of soil heavy metal pollution: geographical explanations beyond artificial intelligence "black box". *Journal of Hazardous Materials, 458,* 131900.

Wen, H., Gui, Z., Tian, C., Xiao, Y., & Fang, L. (2018). Subway opening, traffic accessibility, and housing prices: a quantile hedonic analysis in Hangzhou, China. *Sustainability, 10*, 2254.

Xue, C., Ju, Y., Li, S., & Zhou, Q. (2020). Research on the sustainable development of urban housing price based on transport accessibility: a case study of Xi'an, China. *Sustainability, 12,* 1497.

Yağmur, A., Kayakuş, M., & Terzioğlu, M. (2023). House price prediction modeling using machine learning techniques: a comparative study. *Aestimum, 81*(3), 9-51.

Yang, B., Long, W., Peng, L., & Cai, Z. (2020). Testing the predictability of U.S. housing price index returns based on an IVX-AR model. *Journal of the American Statistical Associaton, 115*(532), 1598-1619.

Yang, Y., Zhang, K., Wang, J., & Nguyen, Q. V. (2015). Cabinet tree: an orthogonal enclosure approach to visualizing and exploring big data. *Journal of Big Data, 2,* 15.

Zhang, P., Zhou, C., Wang, P., Gao, B. J., Xingquan Zhu, X., & Guo, L. (2015). E-tree: an efficient indexing structure for ensemble models on data streams. *IEEE Transactions on Knowledge and Data Engıneerıng, 27,* 2.

Zhang, Y., Liu, J., & Shen, W. (2022). A review of ensemble learning algorithms used in remote sensing applications. *Applied Sciences, 12,* 8654.

Zulkifley, N., Rahman, S., Nor Hasbiah, U., & Ibrahim, I. (2020). House price prediction using a machine learning model: a survey of literature. *International Journal of Modern Education and Computer Science, 12,* 46-54.

Crack Detection of Roads in Karadeniz Technical University Campus with Image Segmentation Method

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Abstract

Deep learning methods have been widely employed in various fields in recent years. In the literature, there are studies that focus on the detection of road cracks using deep learning-based image segmentation methods. This study specifically addresses the applicability of road crack detection through image segmentation methods within the context of Karadeniz Technical University Campus. In this scope, the U-Net architecture, a convolutional neural network model for image segmentation, was utilized for detecting cracks in the roads within the campus. Images of the campus roads were compiled to create a suitable dataset, and the model was trained using this dataset. Upon evaluating the trained model with test images, it was observed that the detection of cracks in the campus roads was successfully achieved with high accuracy in both mathematical and area visualization outputs. Consequently, utilizing data acquired from the road infrastructure of Karadeniz Technical University Campus, a novel application with the U-Net architecture has been employed for the detection of road cracks.

Keywords: *deep learning, image segmentation, road crack detection, u-net.*

Introduction

Cracks are one of the damage types that occur over time in highway infrastructure. Various factors such as exposure to traffic load, soil movements, weather conditions, temperature fluctuations, etc., can lead to cracks of different directions, forms, and sizes on roads. These cracks pose a significant risk factor for traffic safety. Therefore, crack detection on roads is an important issue that should not be overlooked, especially for traffic safety.

Periodic monitoring of cracks on roads helps in early detection. With early detection of cracks, measures can be taken before cracks progress into deeper and wider forms, thus maintaining traffic safety with less risk. Early crack detection is also crucial in terms of maintenance and repair costs. Maintenance and repairs of cracks on roads can be carried out with less cost and labor when cracks are smaller in size. Hence, the early and rapid detection of cracks emerges as a necessity. In recent years, various responses to this necessity have been provided using digital detection methods.

The detection of cracks on roads using artificial intelligence through digital methods has become quite popular in recent years. Crack segmentation has been addressed using traditional image processing methods, followed by the development of deep learning methods, which have yielded more efficient outputs in crack segmentation. In this study, crack detection on roads was conducted using deep learning-based image segmentation with U-Net network. In this context, studies conducted using deep learning-based image segmentation in the literature have been examined, solely. Cheng et al. (2018) undertook a seminal investigation employing a deep learning-based image segmentation methodology within the framework of the U-Net architecture for the purpose of crack segmentation. Following this study, researchers evaluated the crack detection performance of the new networks they developed by making some layer changes in the U-Net network (Di Benedetto et al., 2023; Hong et al., 2022; Wu et al., 2023). Furthermore, there exist studies that adopt architectures formulated and labeled by researchers leveraging the U-Net design to attain robust crack detection outcomes. Illustratively, notable instances encompass R2-AENet (Li et al., 2023), HC-Unet++ (Cao et al., 2023), U-VGG19 (Rill-García et al., 2022), MRA-UNet (Gao & Tong, 2023), PDDNet (Zhong et al., 2024), CU-Net, and FU-Net (Gao et al., 2019), among others. In addition, as well as the U-Net architecture, different model proposals have been encountered that are created with their own network structures and can achieve efficient results in detecting road cracks. These proposals encompass the segmentation model named FPHBN, conceived by Yang et al. (2020), the DBPNet model advocated by Wang et al. (2023), and the Shuff-BiseNet network model (Wang et al., 2023). Literature also encompasses studies engaging in crack detection using segmentation networks diverging from the U-Net framework. For instance, Ji et al. (2021) performed crack detection on road surfaces employing the DeepLabv3+ architecture, while concurrently contributing a study centered on the precise measurement of crack dimensions. Another model, ParallelResNet, proposed by Fan et al. (2022), concentrates on crack measurement alongside crack detection. In their study, Chong et al. (2024) not only focused on detecting cracks and sizing them but also provided insights into repair and maintenance strategies for cracks. In this regard, this study has emphasized determining feasible crack maintenance strategies and investigating maintenance costs utilizing the U-Net network. Lastly, the study by Qiu et al. (2023) stands out within the research landscape due to its utilization of a distinct image typology. This study presents a method tailored for extracting cracks in infrared images of pavement surfaces, drawing inspiration from the U-Net and ResNet-34 network architectures.

Methodology

In this study, deep learning-based image segmentation method is used to detect the cracks that have occurred over time on the roads in Karadeniz Technical University Campus. The steps of the study are determined as data collection, image masking, model training and model testing as shown in Figure 1.

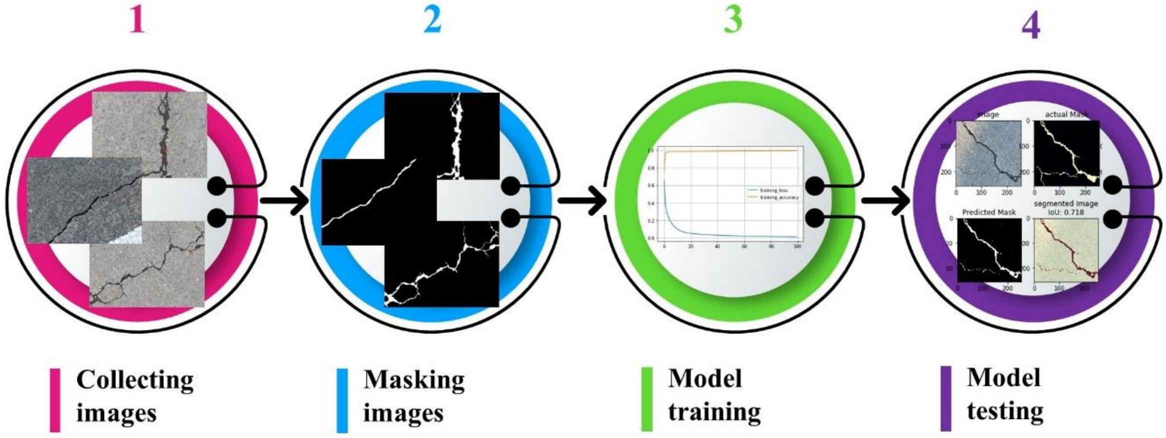


Figure 1: The methodology of the study.

Data Collection

A total of 500 crack images were obtained from the roads in Karadeniz Technical University Campus to be used in the training and testing phases of the model (Figure 2). These images were taken with the Smartphone Xiaomi Redmi Note 8 Pro which has 64 MP camera resolution feature with the help of the setup shown in Figure 3. While obtaining the images, the height of the setup from the ground was determined as 97 cm and this height is taken constant in each photograph. The area of each image was determined as 61,25 cm x 45,5cm. Out of 500 images, 450 images are used for model training and 50 images are used for model testing. At this point, the images constituting the dataset are randomly distributed, with 90% allocated for training and 10% for testing. All images used in the study are taken personally by the authors.

Figure 2: Sampling of crack images obtained from the roads in Karadeniz Technical University Campus.

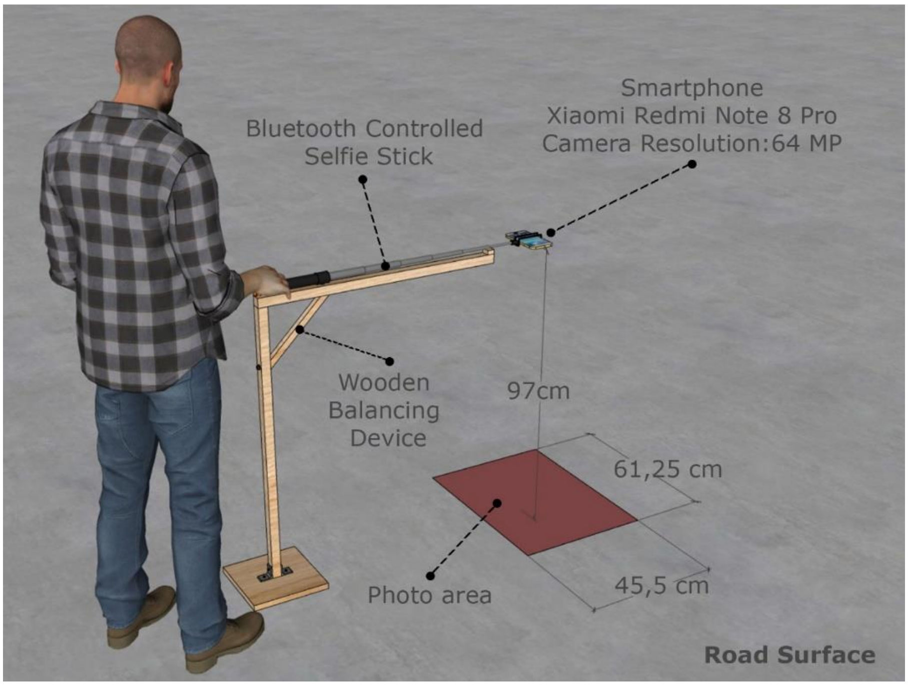
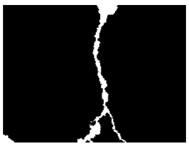


Figure 3: Visualization of the setup.

Image Masking

The training dataset used for model training consists of input and output images. Original images containing cracks on the roads within the campus are utilized as inputs, while their masked images serve as outputs. Masked images were obtained by identifying and painting the crack areas in the original images. Accordingly, cracks present in all road images are painted white, while the rest of the image is painted black. Examples of original images and the masked images obtained by painting the cracks are provided in Table 1.

Table 1. Examples of original images and masked images of the roads in KTÜ Campus.

Original images					
Masked images					

Accuracy Assessment

There are various measurement metrics used to evaluate model performance. In this study, three different measurement metrics have been employed to assess model performance: accuracy, loss, and intersection over union (IoU). These measurement metrics can take values between 0 and 1. Accuracy denotes the ratio of correctly identified instances by the algorithm to all instances. As the accuracy value approaches 1, it is observed that the model's prediction ability improves. Loss is defined as the measurement metric that gives the difference between the true value and the value predicted by the model. Unlike the accuracy metric, as the loss value approaches 0, it is observed that the model's prediction ability improves. The IoU metric represents the ratio of the intersections of the combination of the class space determined by the algorithm and the class space that is actually true. Similar to the accuracy metric, as the IoU metric value approaches 1, it is observed that the model's prediction ability improves (Semercioğlu, 2022).

Results and Discussion

Model Training

Google Colab Notebook with virtual GPU, a free cloud service, is used for the training of the model. Colab is powered by Intel Xeon Processor with two cores @ 2.20 GHz and 13GB RAM. The model is trained with 450 images allocated for model training. In the study, the epoch is determined as 50 and the particle size is determined as 16. The analysis is trained in 8 minutes.

The graph depicting the accuracy-loss values achieved as a result of model training through analysis is shown in Figure 4. In this graph, the orange curve represents the training accuracy, while the blue curve represents the training loss rate. The loss-accuracy values reached by the analysis as a result of model training are presented in Table 2. Evaluation of the attained accuracy-loss values indicates that the model exhibits high predictive capability.

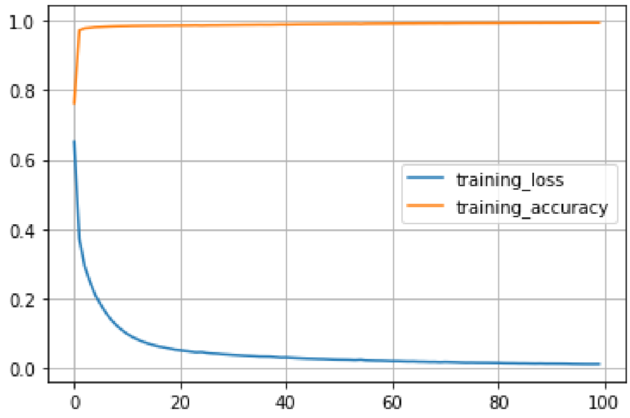


Figure 4: Loss-accuracy graph of analysis.

Table 2. Loss and accuracy values of analysis.

	Training values
Loss	0,0104
Accuracy	0,9951

In Figure 5, original image samples from the training data are juxtaposed with masked and predicted image samples for comparison. The images are compiled from samples reaching various IoU values. The model's average validated IoU value achieved with the training dataset is calculated as 0.92. This value, nearing 1, demonstrates that the model possesses a significantly high predictive capability.

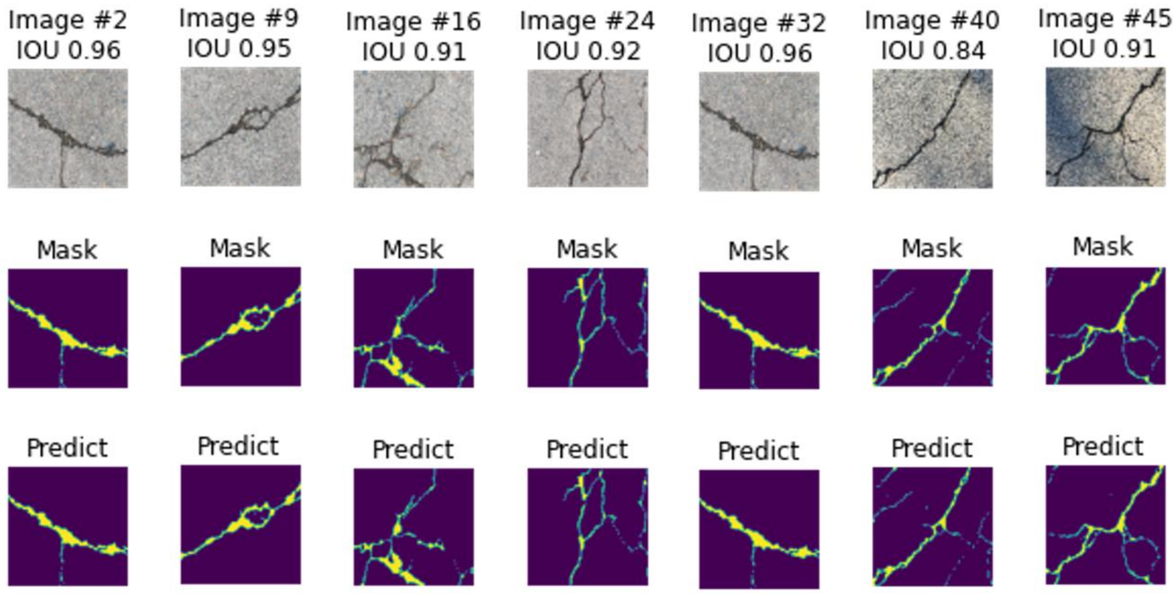


Figure 5: Original, masked and predicted image samples of analysis.

Model Testing

A test dataset consisting of 50 images was created to evaluate the performance of the trained model, and the model was tested with these images. In order to achieve a more objective evaluation, particular attention was paid to ensuring that the images composing the dataset were unseen by the model before. The measurement metric considered in the test evaluations is the average validate IoU metric. The analysis found the test average validation IoU value to be 0.69. Upon examining the average validation IoU values captured by the model during training and testing phases, it is once again evident that the model's predictive ability is quite high. Although the test average validation IoU value (0.69) falls short of the average validation IoU value during training (0.92), it still demonstrates a successful outcome. If the number of images composing the test dataset is increased, the test average validation IoU value will approach the training average validation IoU value even more closely. The outputs obtained by the model in the test are presented in Figure 6.

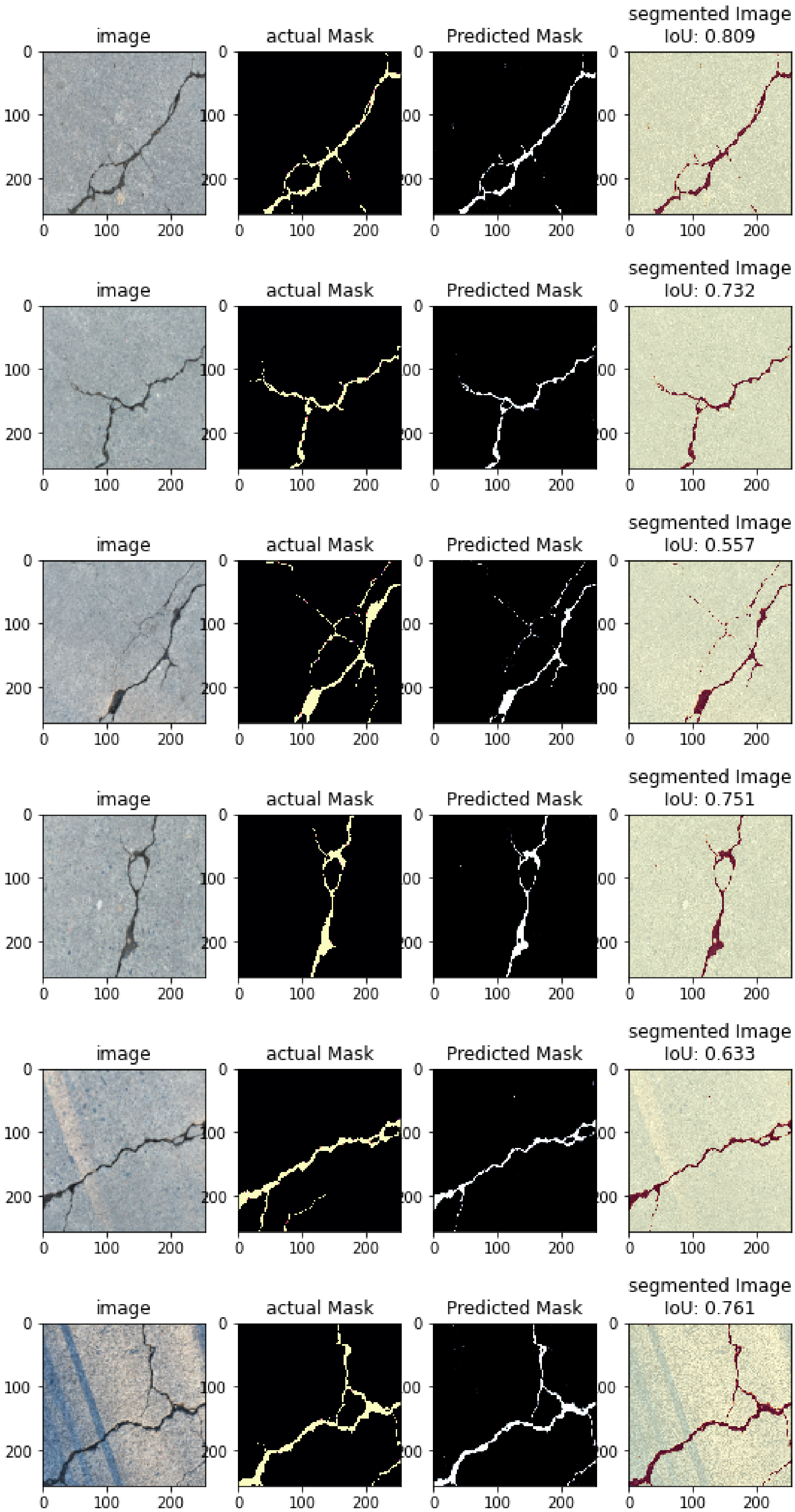


image
actual Mask
Predicted Mask
segmented Image
IoU: 0.809
image
actual Mask
Predicted Mask
segmented Image
IoU: 0.732
image
actual Mask
Predicted Mask
segmented Image
IoU: 0.557
image
actual Mask
Predicted Mask
segmented Image
IoU: 0.751
image
actual Mask
Predicted Mask
segmented Image
IoU: 0.633
image
actual Mask
Predicted Mask
segmented Image
IoU: 0.761

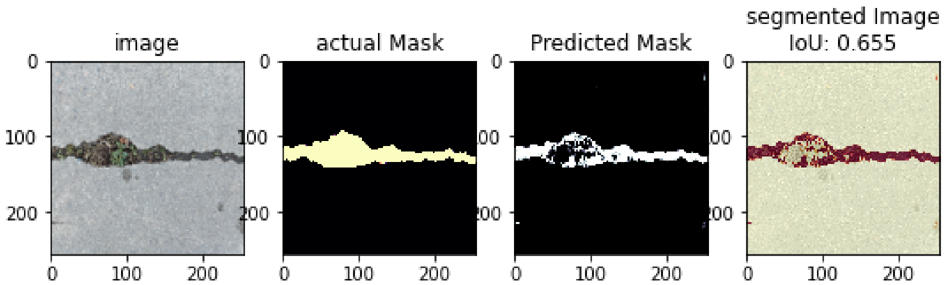


Figure 6: Results of test images for analysis.

Conclusions

In this study, automatic detection of cracks that have formed over time on the roads within the Karadeniz Technical University Campus was carried out using a deep learning-based segmentation method. In this context, the U-Net architecture was utilized. The findings of the study have demonstrated the successful applicability of the U-Net architecture in detecting cracks on the roads within the Karadeniz Technical University Campus. The automatic detection of cracks on campus roads can be evaluated by the university authorities, especially in situations requiring immediate repair or during periodic road maintenance periods. In the future, the scope of this study can be expanded to include the calculation of crack sizes using the data obtained from campus pathways, in addition to crack detection. Also, the most economical scenarios for maintenance and repair costs of these cracks can also be examined.

References

Cao, H., Gao, Y., Cai, W., Xu, Z., & Li, L. (2023). Segmentation detection method for complex road cracks collected by UAV based on HC-Unet++. *Drones*, *7*(3), 189.

Cheng, J., Xiong, W., Chen, W., Gu, Y., & Li, Y. (2018). Pixel-level crack detection using U-Net. *Proceedings of TENCON - IEEE Region 10 Conference* (pp. 0462-0466). IEEE.

Chong, D., Liao, P., & Fu, W. (2024). Multi-objective optimization for sustainable pavement maintenance decision making by integrating pavement image segmentation and TOPSIS methods. *Sustainability*, *16*(3), 1257.

Di Benedetto, A., Fiani, M., & Gujski, L. M. (2023). U-Net-based CNN architecture for road crack segmentation. *Infrastructures*, *8*(5), 90.

Fan, Z., Lin, H., Li, C., Su, J., Bruno, S., & Loprencipe, G. (2022). Use of parallel ResNet for high-performance pavement crack detection and measurement. *Sustainability*, *14*(3), 1825.

Gao, X., & Tong, B. (2023). MRA-UNet: balancing speed and accuracy in road crack segmentation network. *Signal, Image and Video Processing*, *17*(5), 2093-2100.

Gao, Z., Peng, B., Li, T., & Gou, C. (2019). Generative adversarial networks for road crack image segmentation. *Proceedings of International Joint Conference on Neural Networks* (pp. 1-8). IEEE.

Hong, Z., Yang, F., Pan, H., Zhou, R., Zhang, Y., Han, Y., & Liu, J. (2022). Highway crack segmentation from unmanned aerial vehicle images using deep learning. *IEEE Geoscience and Remote Sensing Letters*, *19*, 1-5.

Ji, A., Xue, X., Wang, Y., Luo, X., & Wang, L. (2021). Image-based road crack risk-informed assessment using a convolutional neural network and an unmanned aerial vehicle. *Structural Control and Health Monitoring*, *28*(7), e2749.

Li, G., Xin, Y., Shen, D., Wang, B., Deng, Y., & Zhang, S. (2023). Automatic road crack detection and analysis system based on deep feature fusion and edge structure extraction. *International Journal of Pavement Engineering*, *24*(1), 2246096.

Qiu, D., Xiao, M., Wan, S., Qin, C., & Zhu, Z. (2023). Pavement crack detection in infrared images using a DCNN and CCL algorithm. *IEEE Sensors Journal*, *23*(5), 4548-4555.

Rill-García, R., Dokládalová, E., & Dokládal, P. (2022). Pixel-accurate road crack detection in presence of inaccurate annotations. *Neurocomputing*, *480*, 1-13.

Semercioğlu, İ. N. (2022). *Automatic detection of helmet usage in construction site with deep learning methods* [Master thesis]. Karadeniz Technical University.

Wang, H., Wang, B., & Zhao, T. (2024). Shuff-BiseNet: a dual-branch segmentation network for pavement cracks. *Signal, Image and Video Processing*, 1-12.

Wang, P., Zhu, J., Zhu, M., Xie, Y., He, H., Liu, Y., & You, J. (2023). Fast and accurate semantic segmentation of road crack video in a complex dynamic environment. *International Journal of Pavement Engineering*, *24*(1), 2219366.

Wu, Q., Song, Z., Chen, H., Lu, Y., & Zhou, L. (2023). A highway pavement crack identification method based on an improved U-Net model. *Applied Sciences*, *13*(12), 7227.

Yang, F., Zhang, L., Yu, S., Prokhorov, D., Mei, X., & Ling, H. (2019). Feature pyramid and hierarchical boosting network for pavement crack detection. *IEEE Transactions on Intelligent Transportation Systems*, *21*(4), 1525-1535.

Zhong, J., Zhang, M., Ma, Y., Xiao, R., Cheng, G., & Huang, B. (2024). A multitask fusion network for region-level and pixel-level pavement distress detection. *Journal of Transportation Engineering, Part B: Pavements*, *150*(1), 04024002.

Strategies for Digital Transformation in Construction Industry

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Abstract

Today, the construction industry is faced with increasingly complex projects, creating the need for more effective and efficient processes. These challenges highlight the construction industry's need for digital transformation. Digital transformation moves the construction industry away from traditional business models and allows it to evolve towards a more innovative and technology-driven future. This evolution enables stakeholders in the sector to realize more effective, efficient and sustainable projects. In addition, digital transformation provides positive contributions to the construction industry such as cost reduction, process improvements, productivity and quality increases. Despite these positive contributions, the construction industry is known to be resistant to adopting digital transformation. At this point, studies that reveal the strategies that will enable adaptation to digital transformation for the construction sector, where the impact of digitalization remains low compared to other sectors, gain importance. This study aims to summarize effective strategies to promote digital transformation for Turkish construction industry through a comprehensive literature review. The study which identifies strategies not only only has the potential to guide stakeholders in the sector in their digital transformation journey but also aims to make significant contributions to the studies on strategies that will support adaption to digital transformation in the construction sector.

Keywords: *construction industry, digitalization, digital transformation, strategy, technology.*

Introduction

In order to properly understand and position the concept of digital transformation, it is important to define it. Currently, there is no generally accepted definition of digital transformation. Moreover, the concepts of digitalization and digitization are used interchangeably with digital transformation (Schallmo et al., 2017). However, Verhoef et al. (2021) defined these concepts as stages of digital transformation. According to this definition, digital transformation consists of three stages. These are digitization, digitalization and digital transformation.

Digital transformation is the process of reshaping and improving the business processes of businesses and society by using digital technologies with the advancement of technology.

Furjan et al. (2020) defines digital transformation as a technology-driven change process and refers to digital technology-based improvements in business processes. As a highly influential concept and process, digital transformation can transform all areas of human life, significantly impacting markets such as the construction industry, where digital technologies are highly utilized (Wang et al., 2022). In the construction industry, digitalization is often applied in construction projects, representing the stage of necessity to move towards company and industry-wide digital transformation (Wernicke et al., 2023). Adekunle et al. (2021) explained the purpose of digital transformation as increasing construction output and efficiency to achieve project outcomes and better customer satisfaction, and stated that digital transformation in the construction industry will occur through the adoption of information, informatic, communication and connectivity technologies. Zhang et al. (2023) defined digital transformation in the construction industry as the process of implementing digital technology to promote digital changes in production methods and organizational models across the industry.

In the digital age we live in, it is unthinkable that the construction industry will not be affected by digital transformation. A number of challenges in the construction industry, such as the complexity of projects, the presence of a large number of stakeholders, the multiplicity and inconsistency of regulatory resources, the variety of available software and technology, gaps in information systems, and the incompatibility of digitalization plans, necessitate digital transformation (Panenkov et al., 2021). Digital transformation presents a new opportunity to enhance the efficiency of construction organizations by continuously optimizing the entire lifecycle of building products, regardless of the company's role within the production, sales, or service chain (Ivanov & Fedoseeva, 2023). There is a need for resources to guide companies in this process. This study was conducted to identify effective strategies to promote digital transformation in the Turkish construction industry.

Studies on Digital Technologies

Technologies that enable the digital transformation of the construction industry are technologies such as IoT, BIM, VR, AR, big data. There are many studies in the literature on the benefits of these technologies. For example, Shojaei (2019) examined the use of blockchain technology in the construction industry. Bilal et al. (2016) identified the challenges of using big data in the construction industry. Shin & Dunston (2008) presented a comprehensive study identifying augmented reality application areas in the construction industry. Bello et al. (2021) explained the current and future application areas of cloud computing technology in the construction industry, as well as identifying barriers to wider adoption of this technology and strategies to overcome these barriers.

Despite the number of studies on the benefits of digital technologies, a stronger background is needed to realize digital transformation in the construction industry. As Adekunle et al. (2021) argue, digital transformation is not just about digital technologies but affects every aspect of human endeavor. Therefore, digitalization in the construction industry can be successfully realized by addressing social and technical aspects in a comprehensive manner (Liu et al., 2023). At this point, strategies will be a tool to link digital transformation in the construction industry to stakeholder acceptance (Dolla et al., 2023).

Accordingly, this study aims to identify effective strategies to support adaptation to digital transformation in the Turkish construction industry and to provide a resource to guide stakeholders and companies in the industry in their digital transformation processes.

Research Method

The research includes how digital transformation strategies are addressed in the literature, focus groups and semi-structured interviews to understand and impact of strategies on the Turkish construction industry. Research method is shown in the Figure 1.

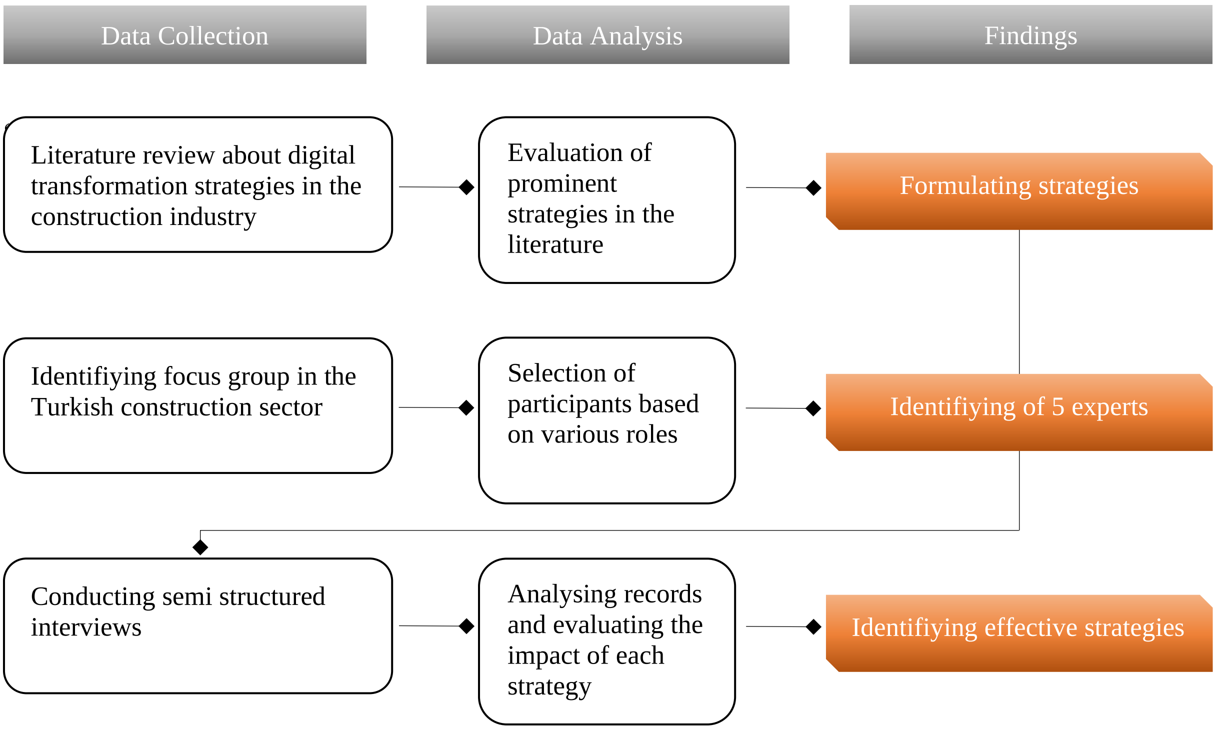

Figure 1: Flow chart of the research.

Identifying digital transformation strategies in literature

This study is based on a recent research that examines digital transformation strategies in depth. Dolla et al. (2023) emphasized the necessity of various strategies in their study on digitalization in the construction industry and proposed 13 strategies. They categorized these strategies under the headings of organization, people, process and data. Based on this study, the literature was examined more extensively, and three different strategies frequently mentioned in different publications were integrated into the study. The first two of them [S1 (Merschbrock & Munkvold, 2015; Suprun & Stewart, 2015; Ezeokoli et al., 2016; Oesterreich & Teuteberg, 2016; Papadonikolaki, 2018) and S2 (Stewart & Mohamed, 2004; Smith, 2014; Suprun & Stewart, 2015; Oesterreich & Teuteberg, 2016; Pan & Pan, 2020; Hwang et al, 2022; Zhang et al., 2023)] are government-related and grouped separately, while the third one S9 (Stewart & Mohamed, 2004; Oesterreich & Teuteberg, 2016; Papadonikolaki, 2018; Aghimien et al., 2020) is included in organization-related strategies. The strategies considered are shown in Table 1.

Experts were then interviewed to understand the implications of these strategies in the context of the Turkish construction sector.

Table 1. Strategies to promote adoption of digital transformation.

Category	Code	Strategy
strategies related to government	S1	standards and legal framework
	S2	financial incentives
strategies related to organization	S3	a long-drawn digitalisation strategy
	S4	mandates and top-down approach
	S5	scout teams and external collaborations
	S6	cross-functional teams
	S7	process champion
	S8	training efforts
	S9	digital partnership
strategies related to people	S10	benefit projection and empathy
	S11	stakeholder integration
	S12	influencing total team climate
strategies related to process	S13	process re-engineering
	S14	customising the requirements
strategies related to data	S15	real-time data-driven problem diagnostics
	S16	federated data

Focus Group

Semi-structured interviews were conducted with industry professionals to understand the impact of the 16 strategies derived from the literature on the Turkish construction industry. In order to obtain a comprehensive perspective, diversity of participants was emphasized to represent the various perspectives, experiences and needs of different groups. Participants were only included if they had experience with digital technologies and digital transformation in the construction industry. Experience and credentials are shown in Table 2 and Table 3. The experience given here in years is the expert's total experience as a practitioner in the construction industry.

Table 2. Information of experts.

Code	Job	Exp. Years	Industry
Expert 1	Civil Engineer	12	Private Sector
Expert 2	Civil Engineer	13	Private Sector
Expert 3	Electrical Engineer	14	Private Sector
Expert 4	Architect	23	Public Sector
Expert 5	Mechanical Engineer	18	Private Sector

Table 3. Summary of experience.

Code	Summary of experience
Expert 1	The expert works as the chairman of the board of a private organization to realize the digitalization of the Turkish construction sector and also as the director of the project management office in one of the leading companies in the sector. Moreover, expert has conducted significant academic studies to prepare and apply Turkey's digital transformation roadmap.
Expert 2	The expert works in the digital transformation department of a project management company in areas such as software research, digital construction technologies and integration of BIM-related processes.
Expert 3	Expert is a co-founder of a company working for digitalization of construction projects. Expert has been involved in the digitalization processes of many domestic and international projects in the three main sub-divisions of the construction sector that is superstructure, infrastructure and energy.
Expert 4	Expert represents the public sector. Expert has worked in various roles in public construction projects for many years. Expert has conducted awareness trainings with organizations leading Turkey's digital transformation in order to spread the awareness of digital processes in the unit where expert worked.
Expert 5	Expert has a wide range of experience in the construction industry, from implementation to project management. Expert has worked on many international projects. Expert is currently working as a general manager in a local company. Expert is the digital transformation director of an organization leading the digitalization of the Turkish construction industry.

Semi- Structured Interviews

Five professionals experienced in digital transformation in the Turkish construction industry were interviewed. For each strategy, the experts were asked about the contribution of the strategy to the digital transformation of the company and were asked to give a score between 1 (very low) and 5 (very high).

Semi-structured interviews were conducted online or face-to-face depending on the availability of the expert. For online interviews, the meeting link from the Zoom application was sent to the participants via e-mail. The interviews were completed in approximately 55-90 minutes. With the approval of the experts, video/audio recordings were taken during the interviews.

Focus Group Findings

In the interviews with experts, strategies were translated into meaningful sentences. For example, for the first strategy, a statement such as *"In order for digital transformation to be successful; standards and legal framework for digital transformation of companies should be established by the government and official organizations."* was quoted. Then, the experts were asked about the contribution of this strategy to a firm that wants to digitalize; they were asked to rate the degree of impact from 1 (very low) to 5 (very high). The scores given by the experts for the strategies are given in Table 4.

Table 4: Grade of experts.

	S1	S4	S16	S3	S8	S6	S15	S5	S7	S11	S12	S9	S13	S2	S10	S14
Exp 1	5	5	5	5	5	4	5	4	5	5	4	4	4	3	2	3
Exp 2	5	5	5	3	4	3	4	4	4	3	4	4	3	4	4	5
Exp 3	4	5	5	5	5	5	5	5	4	5	5	5	5	3	5	5
Exp 4	5	4	5	4	3	5	4	3	4	4	3	4	4	3	3	2
Exp 5	5	5	4	5	5	4	3	4	3	3	4	2	2	4	3	2
Avg	**4,8**	**4,8**	**4,8**	**4,4**	**4,4**	**4,2**	**4,2**	**4**	**4**	**4**	**4**	**3,8**	**3,6**	**3,4**	**3,4**	**3,4**

Experts are agreed about the contribution of strategy S1. Most of the experts consider this strategy to be a major driver as it makes digital transformation mandatory for firms.

For the strategy coded S2, experts are of the opinion that it is supportive of transformation. Expert 3 stated that it is difficult for the government to monitor the use and results of the incentives and supports provided and that this process is comprehensive and complex.

For the strategy coded S3; Expert 1 and Expert 4 found it critical that each company should determine a special road map in accordance with its own business method and dynamics in digitalization processes.

For the strategy coded S4, experts agree that it is an effective strategy. Experts considered that one of the most important driving forces for digital transformation is the determination of senior management. Expert 2 stated that transformation would not be possible without the support of senior managers.

For the strategy coded S5, the experts are in close agreement. Expert 2 argued that in the transformation process, it is more supportive for companies to have these teams within the companies rather than IT experts who do not know the sector-specific problems and processes.

For the strategy coded S6, again the experts were in close agreement. Expert 1 stated that the development of collaborative teams offers companies the opportunity to increase teamwork and perspectives from different disciplines.

For the strategy coded S7, the experts are again similar. The presence of a leader was considered important and effective by the experts due to its contributions such as raising awareness of the teams and managers who will be subject to the process, motivating, supporting and ensuring the progress of the process. Differently, Expert 5 emphasized that digital transformation is not the work of only one part of the company and that the appointment of a leader does not mean that the company can manage the process.

For the strategy coded S8, most of the experts argued that training activities are mandatory for adaptation to the digital transformation process.

There are different opinions for the strategy coded S9. Experts 2 and 3 mentioned that it would contribute positively to firms in terms of sharing risks. Expert 5, on the other hand, did not find it realistic that firms in the construction sector would share too much data with each other, and although he stated that this strategy would contribute to the transformation process such as sharing costs and working with a more professional structure, he evaluated its impact as low.

Experts have different opinions for the strategy coded S10. Expert 3 emphasized that this strategy is the most important strategy, stating that all stakeholders will embrace the transformation process when the benefits they provide to them are conveyed. Experts 1 and 5, on the other hand, approved the benefit transfer part of the strategy, but not the empathy part, and argued that the transformation process should be more prescriptive.

For the strategy coded S11, there are both common and different opinions. Expert 1, who argues that the strategy is effective for the digital transformation of the company, emphasizes that this strategy facilitates compliance with international standards, enabling companies and personnel to compete on a global scale, and that this integration reduces costs such as software and makes it possible to receive more appropriate and quality services. Expert 2 did not see the integration of all stakeholders as critical for the digital transformation of the company; he stated that it would only increase the success of the project.

For the contribution of strategy S12, expert 3 emphasized that it enabled the project to proceed efficiently and thus prevented errors and costly delays in the design, revision and manufacturing processes. Expert 5 stated that team members feel that they are part of a common journey and that it will contribute to creating an environment that encourages collaboration and innovation by moving forward together.

There are different opinions for the strategy coded S13. Experts who found this strategy effective emphasized that it would bring great success and efficiency to the company. In contrast, Expert 5 stated that it is important to blend old processes with new processes, otherwise sudden changes can be risky and disruptive for construction companies.

Some experts evaluated the strategy coded S14 as high impact and some as low impact. Expert 2, who stated that it was high impact, interpreted this strategy as an inevitable situation that is already in the nature of digital transformation. Expert 5 stated that customizations should not be done in the first place, and should be done after using the tools offered by the ecosystem effectively and measuring its success, otherwise it may jeopardize the company and the digital transformation process.

Most experts agreed with the strategy coded S15. Expert 1 stated that this strategy provides great benefit in process management. Expert 5 emphasized the need to define a problem for the process and stated that proper process management integrated with data is important.

For the strategy coded S16, the experts are in consensus. Expert 1 stated that having instant and authorized access to data is the basis of digitalization, which saves time by reducing communication problems, and that centralizing and managing data is of great importance in projects.

Conclusions

The results of this study which was conducted to identify effective strategies for the digitalization of the Turkish construction industry, reveal that digital transformation strategies show variable effects in different categories. In particular, government policies and regulations, organizational structure and data-driven strategies contribute more to digital transformation. Standards and legal framework, mandates and top-down approach, and federated data were highly rated as the most effective strategies. These strategies show that government policies and regulations are an important contributor to digital transformation and that support and guidance from top management is critical for transformation. It is a meaningful finding that standards and legal frameworks are identified as an effective strategy as they support digital transformation by providing a certain order, guidance and obligation. Similarly, goals and policies set by top management can accelerate the digitalization process by increasing employee motivation. A federated database that enables real-time data access is the foundation of digitalization.

Other strategies that play an important role in digital transformation include a long-drawn digitalization strategy and training efforts. These strategies emphasize the importance of a comprehensive roadmap for the transformation process and the development of staff digital skills. A long-drawn digitalization strategy ensures that the process is managed with a specific roadmap. This strategy is an effective strategy as it will enable companies to create a plan for their future goals and determine the steps to achieve these goals. Similarly, training is a way for employees to adapt to the digital transformation process. Through training, employees can see the benefits of the process and can be motivated in this way.

At the same time, organizational and data-driven approaches, such as cross-functional teams and real-time data-driven problem diagnostics, make transformation more effective and demonstrate the powerful impact of organizational structure and data on transformation. Bringing together various disciplines increases the potential to generate innovative solutions and solve complex problems more effectively. These teams combine different perspectives and encourage collaboration for the success of digital transformation projects. Data-driven problem diagnosis makes it possible to instantly identify problems and generate solutions using real-time data analysis. This can increase project efficiency and reduce costs in the construction industry.

On the other hand, strategies in the people and process categories score lower, indicating limited contribution of these areas to digital transformation. These results are surprising. Digital transformation causes radical changes in business processes and requires the adoption of new technologies. It is people who will adopt and disseminate these technologies. Therefore, strategies to encourage the active participation of employees in the process should be considered. Similarly, since transformation will lead to changes in business processes, it is important to know how to manage the process on the digital transformation journey.

The results reveal that the government and top management are influential in the Turkish construction industry. It is understood that legal frameworks and strategic guidance play a major role in the process. On the other hand, looking at the scores given for the strategies in general, it is understood that each of them are important points for digital transformation. This highlights the importance of taking a balanced approach and focusing on all categories in the digital transformation process.

In conclusion, government, organization and data-driven strategies make the greatest contribution to digital transformation. However, since the impact of strategies in the people and process categories is more limited, it is important to adopt a balanced focus on all categories in the digital transformation process.

References

Adekunle, S. A., Aigbavboa, C. O., Ejohwomu, O., Adekunle, E. A., & Thwala, W. D. (2021). Digital transformation in the construction industry: a bibliometric review. *Journal of Engineering, Design and Technology*.

Bello, S. A., Oyedele, L. O., Akinade, O. O., Bilal, M., Davila Delgado, J. M., Akanbi, L. A., Ajayi, A. O., & Owolabi, H. A. (2021). Cloud computing in construction industry: use cases, benefits and challenges. *Automation in Construction*, *122*.

Bilal, M., Oyedele, L. O., Qadir, J., Munir, K., Ajayi, S. O., Akinade, O. O., Owolabi, H. A., Alaka, H. A., & Pasha, M. (2016). Big data in the construction industry: a review of present status, opportunities, and future trends. *Advanced Engineering Informatics,* (30)3, 500-521.

Dolla, T., Jain, K., & Kumar, V. S. (2023). Strategies for digital transformation in construction projects: stakeholders' perceptions and actor dynamics for industry 4.0. *Journal of Information Technology in Construction*, 28, 151-175.

Ezeokoli, F. O., Okolie, K. C., Okoye, P. U., & Belonwu, C. C. (2016). Digital transformation in the Nigeria construction industry: the professionals' view. *World Journal of Computer Application and Technology*, *4*(3), 23-30.

Hwang, B.-G., Ngo, J., & Teo, J. Z. K. (2022). Challenges and strategies for the adoption of smart technologies in the construction industry: the case of Singapore. *Journal of Management in Engineering*, *38*(1).

Ivanov, N., & Fedoseeva, T. (2023). Strategies for successful digitalization of Russian construction enterprises. *AIP Conference Proceedings*, *2791*(1).

Liu, Z., Ding, R., Gong, Z., & Ejohwomu, O. (2023). Fostering digitalization of construction projects through integration: a conceptual project governance model. *Buildings*, *13*(3).

Merschbrock, C., & Munkvold, B. E. (2015). Effective digital collaboration in the construction industry - a case study of BIM deployment in a hospital construction project. *Computers in Industry*, *73*, 1-7.

Oesterreich, T. D., & Teuteberg, F. (2016). Understanding the implications of digitisation and automation in the context of Industry 4.0: a triangulation approach and elements of a research agenda for the construction industry. *Computers in Industry*, *83*, 121-139.

Panenkov, A., Lukmanova, I., Kuzovleva, I., & Bredikhin, V. (2021). Methodology of the theory of change management in the implementation of digital transformation of construction: problems and prospects. *E3S Web of Conferences*, *244*.

Pan, M., & Pan, W. (2020). Stakeholder perceptions of the future application of construction robots for buildings in a dialectical system framework. *Journal of Management in Engineering*, *36*(6).

Papadonikolaki, E. (2018). Loosely coupled systems of innovation: aligning BIM adoption with implementation in Dutch construction. *Journal of Management in Engineering, 34*(6).

Schallmo, D., Williams, C. A., & Boardman, L. (2017). Digital transformation of business models-best practice, enablers, and roadmap. *International Journal of Innovation Management 21*(8).

Shin, D. H., & Dunston, P. S. (2008). Identification of application areas for augmented reality in industrial construction based on technology suitability. *Automation in Construction*, *17*(7), 882-894.

Shojaei, A. (2019). Exploring applications of blockchain technology in the construction industry. *Interdependence between Structural Engineering and Construction Management*.

Smith, P. (2014). BIM implementation - global strategies. *Procedia Engineering*, *85,* 482-492.

Stewart, R. A., & Mohamed, S. (2004). An empirical investigation into the link between information technology implementation barriers and coping strategies in the Australian construction industry.

Stolterman, E., & Fors, A. C. (2004). Information technology and the good life. *IFIP Advances in Information and Communication Technology, 143,* 687-692.

Suprun, E. V., & Stewart, R. A. (2015). Construction innovation diffusion in the Russian Federation barriers, drivers and coping strategies. *Construction Innovation*, *15*(3), 278-312.

Wang, K., Guo, F., Zhang, C., & Schaefer, D. (2022). From industry 4.0 to construction 4.0: barriers to the digital transformation of engineering and construction sectors. *Engineering, Construction and Architectural Management*.

Wernicke, B., Stehn, L., Sezer, A. A., & Thunberg, M. (2023). Introduction of a digital maturity assessment framework for construction site operations. *International Journal of Construction Management*, *23*(5), 898-908.

Zhang, J., Chen, M., Ballesteros-Pérez, P., Ke, Y., Gong, Z., & Ni, Q. (2023). A new framework to evaluate and optimize digital transformation policies in the construction industry: a China case study. *Journal of Building Engineering*, *70*.

Exploring the Role of Common Data Environment in BIM

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Abstract

The construction industry has belatedly turned to digital tools to solve efficiency and productivity issues. Along with numerous advantages, a new challenge has arisen in the form of more complex and uncontrollable data volumes. While serving as a backbone in the industry's digitalization journey, BIM is often perceived as nothing more than a -smart-modeling software, even though it started as a more advanced project and data management "methodology" that could respond to this challenge. To correct this misunderstanding and unlock the true potential of BIM, standards and guidelines have begun to emphasize a new concept that prevents data loss, provides a seamless communication flow and enables a collaborative project atmosphere. Therefore, this paper aims to comprehensively present the interaction of this so-called "common data environment" -or CDE- with BIM and explore its broad applicability and implications. In this way, the concept of a common data environment will be more frequently considered in the industry, and BIM's true purpose will be highlighted. It will also inform researchers and practitioners of the trends and gaps and provide a more profound exchange of ideas in all future research efforts.

Keywords: *building information modeling (BIM), common data environment (CDE), database, information management*

Introduction

The Architecture, Engineering, Construction, and Operation (AECO) industry's bad reputation for productivity and efficiency, backed by reports from global consulting companies such as McKinsey and KPMG, has been recognized by all industry professionals. The construction management literature often attributes this poor reputation to the fact that the industry is low-tech, still based on traditional techniques, and has adopted a traditional management approach that results in high levels of data loss (Choudhry, 2017; Craveiro et al., 2019; Li et al., 2019;

Opoku et al., 2021). Industrial revolutions have facilitated and improved management strategies and manufacturing methods throughout history. Industry 4.0, the current industrial revolution, aims to integrate physical environments with digital ecosystems (Sepasgozar, 2021). With mass production industries finding solutions in information technology for many years to enable better management of their products, the AECO industry has also started to explore digital technologies to overcome its efficiency and productivity issues. (Cimino et al., 2019).

With the adoption of new technologies and the massive increase in data produced on a typical construction project, better management has become necessary. However, neglect of this situation in the industry has led to greater problems in terms of productivity and efficiency in data usage (Ruperto & Strappini, 2021). Additionally, according to Kiu et al. (2024) and Jaskula et al. (2023), another reason for this massive increase in data is that construction projects usually involve a wide range of stakeholders communicating at various phases of the project life cycle. Therefore, effective data management is vital for every construction organization. Fortunately, in the twenty-first century, every professional understands the value of collaboration and the utilization of any data to enhance management procedures. According to Ruperto and Strappini (2021), organizations are progressively operating inside novel collaborative environments to attain elevated standards of excellence and improved efficiency by reusing pre-existing knowledge and expertise. Playing the backbone role in the digitalization journey of the AECO industry, Building Information Modelling (BIM) is a technique for streamlining the building management process by employing a digital, three-dimensional model of the project. BIM, which promotes efficiency by allowing several disciplines to collaborate and manage data in a digital environment, has been extensively discussed in the literature over the past 20 years due to its various options. However, the AECO industry faces several obstacles to fully exploiting BIM’s collaboration and data management potential. At this point, a new concept defined by standards and guidelines, Common Data Environment (CDE), is considered the basis of data management processes in BIM-based project delivery. (Jaskula et al., 2023; BSI, 2021). Nevertheless, the shortage of literature on digital collaboration through CDE makes it more difficult for the AECO industry to strategically encourage the adoption of current and emerging technologies. These problems also point to a lack of knowledge regarding the background of CDE as a strategy for forming an integrated digital collaboration in the industry (Tan et al., 2023).

In light of this, the purpose of this paper is to evaluate the literature on CDE in construction management, to clarify how it interacts with BIM, and to investigate how it may remove barriers to BIM's full potential, which can enhance the industry's poor data management and collaboration environment.

To develop and validate the framework, this paper adopted integrative or critical review as a qualitative research methodology. To foster the emergence of newly developed theoretical frameworks and viewpoints, an integrative review attempts to evaluate, analyze, and synthesize the literature (Torraco, 2005). Since this type of review typically aims to combine perspectives and insights from many fields or research traditions rather than to cover every article ever published on the subject, it frequently calls for a more inventive approach to data collection (Snyder, 2019). In this paper, Scopus was chosen because it outperforms other databases in terms of its wider coverage of scientific articles (Akinlolu et al., 2022; Chadegani et al., 2013), and 29 relevant research papers were utilized using multiple search queries.

Data Management in Construction 4.0

The management of construction projects is an intricate and demanding process by nature. Following the ideas of Industry 4.0, Construction 4.0 can be defined as integrating automation and the latest digital technologies into the AECO industry to enhance management and increase productivity, sustainability, safety, and efficiency. Although it overcomes traditional challenges with its key components such as BIM, internet of things platforms, artificial intelligence, and extended reality technologies, it has also brought with it a new challenge of increased volume, velocity, and variety of data produced and their adequate control, privacy, and security. Inadequate system control results in higher project expenses, longer project timelines, lower productivity, and lost profits. According to Radl and Kaiser (2019), providing accurate and up-to-date data to the person performing the task or process while preventing the data from being unstructured, chaotic, poorly coordinated, and dispersed is crucial.

Building Information Modeling

BIM is one of the most frequently utilized methods in construction projects globally. It makes managing a structure and all its assets easier by using a digital, three-dimensional representation of the building (Akturk, 2022). Goyal et al. (2020) define BIM as designing, constructing, operating, and maintaining a facility effectively and on schedule by exchanging data with stakeholders and project teams through an information-rich 3D model. According to Patacas et al. (2020), BIM tools, procedures, and standards offer the chance to efficiently manage data transfers across the construction project's entire life cycle. Also, according to Seidenschnur et al. (2022), it is the practice of generating and managing clearly specified building data to provide a shared database for stakeholders. From conceptual design to the operation and maintenance phase, it serves as a platform for maintaining an accurate and interoperable record of building information (Khajavi et al., 2019). Moreover, it has made it easy for stakeholders to exchange data, communicate and collaborate in real time (Jang et al., 2021; Onungwa et al., 2021). Along with enhancing data management and maintaining coordination, many researchers worldwide have also identified numerous benefits of BIM, such as fostering a culture of teamwork within project teams to boost profitability, lower costs, optimize time management, and fortify customer relationships; elaborating quality; enhancing productivity; and improving performance throughout the entire construction project life cycle (Chen et al., 2023; Shalaka Hire et al., 2021; Mesároš et al., 2022). During the planning phase, it facilitates the efficient and fast determination of the optimal solution from various options (Li et al., 2012). It saves the project team time by allowing them to assess the space while comprehending the data complexity of space standards and land legislation (Hire et al., 2021). In addition to estimation, site coordination, and constructability analysis applications in the pre-construction phase, it is also utilized in the design phase to improve quality, minimize design errors, missing and clash, and so forth (Hire et al., 2021; Jang et al., 2021). BIM enables project progress tracking during construction using 4D plans, change orders, and punch list data embedded in the model (Hire et al., 2021; Jang et al., 2021). Thus, it allows to represent the construction process virtually, simulate the allocation of costs and resources, update the construction plan regularly, and strengthen the rationality of the construction (Jiang et al., 2021; Akturk, 2022). Since BIM acts as a single intelligent source containing all data of the building and its components such as manufacturer, material, price, supply, etc., its applications in the later phases of the construction project life cycle have been discussed in numerous studies (Coupry et al., 2021; Falcão Silva & Couto, 2021; Fargnoli et al., 2019; Zhou, 2022). Advanced data management improves the performance of facility management, with a particular focus on optimizing maintenance operations.

As the above illustrates, coordination, communication, and collaboration are principles of BIM (Liu et al., 2015). However, despite significant advances and widespread adoption of BIM in the AECO industry, the full potential of BIM for collaborative working and data management is still not being exploited (Wong et al., 2020). The literature has articulated the various factors that cause this. Resistant of construction companies to innovation (Krasovskaya et al., 2022), lack of skilled workforce (Uzairuddin & Jaiswal, 2022), and financial barriers to investment (Georgiadou, 2019) are examples of these factors. Data management and its related challenges are also examined among the most important factors (Hwang et al., 2022). Seidenschnur et al. (2022) claim that issues such as most current workflows being manual or only partially automated and utilizing conventional spreadsheets prevent BIM from being utilized to its full potential. Azhar (2011), on the other hand, raised subjects such as interoperability, data control, data ownership, and contractual concerns such as copyright and licensing issues. Furthermore, during their interviews with maintenance personnel, Ghorbani et al. (2022) mentioned that these issues resulted in data loss during the delivery phases, and BIM was unable to perform its full potential. Data management and collaboration elements at different levels have led to classify BIM's level of maturity.

The degree of BIM implementation and maturity levels are called the collaboration level and collaborative environment. Creating and exchanging data among every stakeholder participating in a project is the basis of collaboration (Odriozola et al., 2022). In other words, BIM-based collaboration between stakeholders is defined by BIM maturity levels (Seidenschnur et al., 2022; Succar et al., 2012). The National Building Specification divides BIM maturity into four levels:

- Level 0 corresponds to almost no collaboration. CAD information is shared from different sources (Brunone et al., 2021).
- Level 1 corresponds to a central repository that enables all data from the project to be stored and exchanged digitally without a common data format. The data can be documents or files created in the BIM environment or not, and in any format (Odriozola et al., 2022).
- Level 2 requires a collaborative flow by implementing common data formats such as IFC in a multidisciplinary 'model-based' collaborative project framework (Brunone et al., 2021; Succar et al., 2012).
- Finally, level 3 corresponds to the maximum degree of collaboration with full integration, where all stakeholders collaborate with a common model in a network-based CDE (Seidenschnur et al., 2022). At this stage, the object-based models are shared with at least two other disciplines via CDE linked to external databases (Succar et al., 2012).

Common Data Environment

It is impossible to discuss BIM without considering the guidelines and standards that allow users to develop and implement BIM efficiently and consistently (Liu et al., 2015; Odriozola et al., 2022). The ISO 19650 series is an international standard that outlines requirements and principles for data management throughout the life cycle of a construction project in the AECO industry. It is closely related to BS1192 and PAS 1192, which were withdrawn in 2018. The British Standards Institution released BS 1192:2007 to offer guidelines that facilitate collaboration by outlining the rules for data modeling, exchange, and publication (Liu et al., 2015). The data management is outlined in PAS 1192-2 and PAS 1192-3, respectively. These standards apply to all stakeholders gathering and using data throughout a construction project.

A common working scenario for data management, defined as a CDE in ISO 19650, is a minimum requirement for multidisciplinary collaboration (Schimanski et al., 2021). This allows model collaboration to be supported by following predefined protocols. ISO 19650 addresses the BIM-based delivery of AECO projects with two parts: project management and information delivery. According to Preidel et al. (2018), project management covers all the procedures required to initiate a BIM project and the subsequent contractual and tendering procedures, including creating the BIM Execution Plan. In contrast, information delivery covers all the procedures required for creating and delivering a model, including using a CDE. CDE is a central repository for creating, managing, evaluating and sharing construction project data. It keeps track of every domain-specific partial model and document required for project collaboration and execution, and all project stakeholders collect input data from the CDE and store their output data in it (Preidel et al., 2018). The CDE's contents are not restricted to assets made in "BIM environments." It consists of documentation, graphical and non-graphical assets (Akob et al., 2019). By establishing bi-directional connections between the database model and simulation services, CDE ensures that stakeholders use the most up-to-date model to simulate or make decisions (Seidenschnur et al., 2022). It allows the creation of a shared workspace, a plan for data exchange, granting roles and permissions, and collaboration (Odriozola et al., 2022). To provide a more understandable definition of CDE, Bedoiseau et al. (2022) have developed a 4-level classification (Jaskula et al., 2023): Level 0 is a pre-version beyond digital solutions; Level 1 is defined as an EDMS that does not provide direct BIM editing but meets ISO19650 requirements; Level 2 is defined as a developed level since it has additional capabilities like clash detection, multidisciplinary collaboration, BIM editing, and a version-control system for workflows involving inspections and authorization; a unified, multidisciplinary BIM model that facilitates model creation and editing as well as synchronous communication within the system is defined as a Level 3 CDE.

The primary goal of the CDE is to foster continuous collaboration by acting as a data management system while simultaneously being an accessible platform for seamless data exchange. To accomplish this goal, all stakeholders must adopt policies and techniques to guarantee the quality of the data in the system. Most important, according to Preidel et al. (2018), is the assignment of formal states to individual data elements and the definition of quality control policies performed following each state change to manage the maturity and reliability of data provided appropriately. In addition to data quality, Ruperto and Strappini (2021) argue that data transparency, reducing data redundancy, and mitigating the risks associated with data duplication are issues that need to be approached sensitively by stakeholders. Odriozola et al. (2022) explained the requirements that CDE should fulfil according to ISO 19650 in 8 items: Each data container has a unique ID and its authorship; each file is graded according to its status (work in progress, shared work, published work, archived work); each file is graded according to its revision; each file is graded according to its classification; the working directory is properly structured into folders; the delivery plan is specified, reflecting important agreed dates or milestones; there are compatible data exchange formats; and each of the roles involved in the project is identified to whom the relevant permissions will be granted. In addition, Vlasák and Čerbák (2019) also noted that the ability to display an infinite number of data reference models in a particular collaboration view and the capacity to use the CDE environment itself to display models primarily in IFC format is an emerging requirement.

Discussion

According to Goyal et al. (2020), it is different from what has been accomplished in the current construction process method to have all the information required for the project created, distributed, and centrally stored. However, to achieve this development and effectively link construction operations, use the data in both directions and coordinate the entire project digitally, there needs to be a high degree of interconnection and compatibility across the various applications project stakeholders use. BIM is designed as a construction methodology that offers numerous advantages for data management, enabling collaboration, coordination, and compatibility between stakeholders to be carried out in a common database throughout the construction project life cycle (Azhar, 2011; Jang et al., 2021; Khajavi et al., 2019; I. O. Onungwa et al., 2017; Patacas et al., 2020; Seidenschnur et al., 2022). However, as revealed in this study, the literature shows that the full potential of BIM for collaborative working and data management is still not being exploited due to various factors (Georgiadou, 2019; Ghorbani et al., 2022; Hwang et al., 2022; Krasovskaya et al., 2022; Uzairuddin & Jaiswal, 2022; Wong et al., 2020). Thus, BIM is trying to move the AECO industry forward as an innovation that has gone beyond its original design purpose and fallen short of its potential. This situation leads to the implementation of BIM at different maturity levels, causing data losses and interruptions in collaboration.

CDE serves as the basis for a clear framework for collaboration and data management among all project stakeholders. For an appropriate BIM implementation, literature contends that CDE features like file naming or folder structure arrangements, automating reviews and approvals, assigning roles and responsibilities, connecting structured and unstructured data and requests, availability of data created in various formats, and creation of audit trails are essential (Akob et al., 2019; Odriozola et al., 2022). Many of the data management shortcomings in BIM can be addressed by having a framework for validating, managing, and updating data within an integrated CDE approach that facilitates operations (Ghorbani et al., 2022). CDE minimizes the likelihood of data redundancy, guarantees the availability of the latest data at all times, increases the pace at which information can be reused, and makes the process of aggregating model knowledge easier (Preidel et al., 2018). It saves time in creating, verifying, and accessing project data, improves quality consistency of all project outputs, makes the most use of the workforce, distributes work across stakeholders, and assists in achieving project deadlines. (Akob et al., 2019). It facilitates stakeholder communication while lowering the likelihood of dispute, improves data transparency, enables effective and precise decision-making, and resolves problems regarding data interoperability (Tan et al., 2023). Critically, these findings align with the topics where BIM falls short on data management. Furthermore, it supports the idea that CDE is the foundation of data management in BIM-based project delivery as defined in the ISO19650 standard. It can be argued that having this level of collaboration with CDE is the most critical way to overcome the barriers to unlocking the potential of BIM.

Conclusion

The inherent complexity of construction projects and the increasing amount of data throughout their lifecycle, especially in recent decades, has made effective data management the key to successful construction management. The research described in this paper aimed at enhancing BIM-based project delivery processes by presenting the interaction of common data environment with BIM and exploring its broad applicability and implications. In this manner, the frequency of CDE consideration and the level of awareness in the industry will be increased.

BIM, whose primary emphasis is to provide an enhanced interdisciplinary collaboration environment for the AECO industry, overcomes the challenges experienced by the industry more easily towards this goal with common data environment approach. Offering the opportunity to adequately and efficiently coordinate multiple databases and collaborate with project stakeholders under one roof throughout the whole life cycle of a construction project, CDE should be considered an integral element in BIM-based project delivery. CDE adds economic, social, and ethical value to the industry's current data management and collaboration processes. In proper sequence, it solves the efficiency and effectiveness challenges the AECO industry faces.

Although it seems to answer many questions in the AECO literature compared to existing methods, including BIM for data management, questions should be sought regarding CDE in practice in future studies: What is the current status, what problems are encountered, and what might the solutions be?

References

Akinlolu, M., Haupt, T. C., Edwards, D. J., & Simpeh, F. (2022). A bibliometric review of the status and emerging research trends in construction safety management technologies. *International Journal of Construction Management*, *22*(14), 2699–2711.

Akob, Z., Zaidee, M., Hipni, A., & Koka, R. (2019). Coordination and collaboration of information for Pan Borneo Highway (Sarawak) via common data environment (CDE). *IOP Conference Series: Materials Science and Engineering*, *512*(1), 012001.

Akturk, B. (2022). *Digital twin for enhanced construction project management during construction*. MSc Thesis submitted at Istanbul Technical University.

Azhar, S. (2011). Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry. *Leadership and Management in Engineering*, *11*(3), 241–252.

Bedoiseau, M., Martin, D., & Boton, C. (2022). Use of KROQI as a Level-2 common data environment in the French construction industry. *Sustainability, 14*(16), 10455.

Brunone, F., Cucuzza, M., Imperadori, M., & Vanossi, A. (2021). From cognitive buildings to digital twin: The frontier of digitalization for the management of the built environment. *Springer Tracts in Civil Engineering*, 81–95.

BSI. (2021). *Organization and Digitisation of Information about Buildings and Civil Engineering Works, Including Building Information Modelling (BIM). Information Management Using Building Information Modelling. Part 1: Concepts and Principles*. British Standards Institution.

Chadegani, A. A., Salehi, H., Yunus, M. M., Farhadi, H., Fooladi, M., Farhadi, M., & Ebrahim, N. A. (2013). A comparison between two main academic literature collections: Web of Science and Scopus databases. *Asian Social Science*, *9*(5), 18–26.

Chen, S., Zeng, Y., Majdi, A., Salameh, A. A., Alkhalifah, T., Alturise, F., & Ali, H. E. (2023). Potential features of building information modelling for application of project management knowledge areas as advances modeling tools. *Advances in Engineering Software*, *176*, 103372.

Choudhry, R. M. (2017). Achieving safety and productivity in construction projects. *Journal of Civil Engineering and Management*, *23*(2), 311–318.

Cimino, C., Negri, E., & Fumagalli, L. (2019). Review of digital twin applications in manufacturing. *Computers in Industry*, *113*, 103130.

Coupry, C., Noblecourt, S., Richard, P., Baudry, D., & Bigaud, D. (2021). BIM-Based digital twin and XR devices to improve maintenance procedures in smart buildings: A literature review. *Applied Sciences (Switzerland)*, *11*(15).

Craveiro, F., Duarte, J. P., Bartolo, H., & Bartolo, P. J. (2019). Additive manufacturing as an enabling technology for digital construction: A perspective on Construction 4.0. *Automation in Construction*, *103*, 251–267.

Falcão Silva, M. J., & Couto, P. (2021). Facility and asset management on BIM methodology. *Advances in Science, Technology and Innovation*, 75–79.

Fargnoli, M., Lleshaj, A., Lombardi, M., Sciarretta, N., & Di Gravio, G. (2019). A BIM-based PSS approach for the management of maintenance operations of building equipment. *Buildings*, *9*(6), 139.

Georgiadou, M. C. (2019). An overview of benefits and challenges of building information modelling (BIM) adoption in UK residential projects. *Construction Innovation*, *19*(3), 298–320.

Ghorbani, Z., Napolitano, R., Dubler, C., & Messner, J. (2022). Evaluating facility asset information needs in a common data environment to support maintenance workers. *Construction Research Congress 2022: Computer Applications, Automation, and Data Analytics - Selected Papers from Construction Research Congress 2022*, *2*, 1184–1190.

Goyal, L. K., Chauhan, R., Kumar, R., & Rai, H. S. (2020). Use of BIM in development of smart cities: A Review. *IOP Conference Series: Materials Science and Engineering*, *955*(1).

Hire, S., Sandbhor, S., Ruikar, K., & Amarnath, C. B. (2021). BIM usage benefits and challenges for site safety application in Indian construction sector. *Asian Journal of Civil Engineering*, *22*(7), 1249–1267.

Hwang, B.-G., Ngo, J., & Teo, J. Z. K. (2022). Challenges and strategies for the adoption of smart technologies in the construction industry: The Case of Singapore. *Journal of Management in Engineering*, *38*(1), 05021014.

Jang, K., Kim, J. W., Ju, K. B., & An, Y. K. (2021). Infrastructure BIM platform for lifecycle management. *Applied Sciences (Switzerland)*, *11*(21).

Jaskula, K., Papadonikolaki, E., & Rovas, D. (2023). Comparison of current common data environment tools in the construction industry. *Proceedings of the European Conference on Computing in Construction*, *4*, Heraklion.

Jiang, F., Ma, L., Broyd, T., & Chen, K. (2021). Digital twin and its implementations in the civil engineering sector. *Automation in Construction*, *130*, 103838.

Khajavi, S. H., Motlagh, N. H., Jaribion, A., Werner, L. C., & Holmstrom, J. (2019). Digital twin: Vision, benefits, boundaries, and creation for buildings. *IEEE Access*, *7*, 147406–147419.

Kiu, M. S., Lai, K. W., Chia, F. C., & Wong, P. F. (2024). Blockchain integration into electronic document management (EDM) system in construction common data environment. *Smart and Sustainable Built Environment*, *13*(1), 117–132.

Krasovskaya, O. A., Vyaznikov, V. E., & Mamaeva, A. I. (2022). Application of BIM technologies as IT projects for digital transformation in industry. *Lecture Notes in Networks and Systems*, *432 LNNS*, 104–116.

Li, H., Chan, N. K. Y., Huang, T., Skitmore, M., & Yang, J. (2012). Virtual prototyping for planning bridge construction. *Automation in Construction*, *27*, 1–10.

Li, J., Greenwood, D., & Kassem, M. (2019). Blockchain in the built environment and construction industry: A systematic review, conceptual models and practical use cases. *Automation in Construction*, *102*, 288–307.

Liu, Z., Osmani, M., Demian, P., & Baldwin, A. (2015). A BIM-aided construction waste minimization framework. *Automation in Construction, 59*, 1-23.

Mesároš, P., Mandičák, T., & Behúnová, A. (2022). Use of BIM technology and impact on productivity in construction project management. *Wireless Networks*, *28*(2), 855–862.

Odriozola, S., Manchado, C., Gomez-Jauregui, V., & Otero, C. (2022). Requirements of a common data environment (cde) study case of VIRCORE. *Lecture Notes in Mechanical Engineering*, 30–37.

Onungwa, I. O., Uduma-Olugu, N., & Igwe, J. M. (2017). Building information modelling as a construction management tool in Nigeria. *WIT Transactions on the Built Environment*, *169*, 25–33.

Onungwa, I., Olugu-Uduma, N., & Shelden, D. R. (2021). Cloud BIM technology as a means of collaboration and project integration in smart cities. *SAGE Open*, *11*(3).

Opoku, D. G. J., Perera, S., Osei-Kyei, R., & Rashidi, M. (2021). Digital twin application in the construction industry: A literature review. *Journal of Building Engineering*, *40*.

Patacas, J., Dawood, N., & Kassem, M. (2020). BIM for facilities management: A framework and a common data environment using open standards. *Automation in Construction*, *120*, 103366.

Preidel, C., Borrmann, A., Mattern, H., König, M., & Schapke, S. E. (2018). Common data environment. *Building Information Modeling: Technology Foundations and Industry Practice*, 279–291.

Radl, J., & Kaiser, J. (2019). Benefits of implementation of common data environment (CDE) into construction projects. *IOP Conference Series: Materials Science and Engineering*, *471*(2), 022021.

Ruperto, F., & Strappini, S. (2021). Complex works project management enhanced by digital technologies. *WIT Transactions on the Built Environment*, *205*, 235–248.

Schimanski, C. P., Monizza, G. P., & Matt, D. T. (2021). The role of common data environments as enabler for reliabe digital lean construction management. *IGLC 2021 - 29th Annual Conference of the International Group for Lean Construction - Lean Construction in Crisis Times: Responding to the Post-Pandemic AEC Industry Challenges*, 97–106.

Seidenschnur, M., Kücükavci, A., Fjerbæk, E. V., Smith, K. M., Pauwels, P., & Hviid, C. A. (2022). A common data environment for HVAC design and engineering. *Automation in Construction*, *142*, 104500.

Sepasgozar, S. M. E. (2021). Differentiating digital twin from digital shadow: Elucidating a paradigm shift to expedite a smart, sustainable built environment. *Buildings*, *11*(4), 151.

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, *104*, 333–339.

Succar, B., Sher, W., & Williams, A. (2012). Measuring BIM performance: Five metrics. *Architectural Engineering and Design Management*, *8*(2), 120–142.

Tan, Y. J., Maaz, Z. N., Bandi, S., & Palis, P. A. (2023). Common data environment: Bridging the digital data sharing gap among construction organizations. *Lecture Notes in Networks and Systems*, *584*, 333–342.

Torraco, R. J. (2005). Writing integrative literature reviews: Guidelines and examples. *Human Resource Development Review, 4*(3), 356–367.

Uzairuddin, S., & Jaiswal, M. (2022). Digital monitoring and modeling of construction supply chain management scheme with BIM and GIS: An overview. *Materials Today: Proceedings*, *65*, 1908–1914.

Vlasák, P., & Čerbák, B. (2019). BIM, structural analysis and communication using common data environment (CDE) in the field of water management. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, 42*(5), 93–94.

Wong, J. H., Rashidi, A., & Arashpour, M. (2020). Evaluating the impact of building information modeling on the labor productivity of construction projects in Malaysia. *Buildings*, *10*(4), 66.

Zhou, Z. (2022). An intelligent bridge management and maintenance model using BIM technology. *Mobile Information Systems, 2022*.

Real-Virtual Synchronization Through BIM and Digital Twin: Current Status and Future Prospects

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Abstract

The purpose of this study is to review real-virtual synchronization through Building Information Modeling (BIM) and Digital Twin (DT) in the Architecture, Engineering, and Construction (AEC) industry. BIM and the Internet of Things (IoT) can be considered technological innovations in the AEC industry as they have the ability to provide real-time connectivity. Yet, providing a shareable and consistent database throughout the design and construction processes, BIM cannot automatically update real-time information. The DT transfers real-time data to the digital model for continuous improvement of projects and synchronization of the real-virtual environment throughout the construction process. In this study, a literature search and content analysis were conducted to identify the current status and future prospects, focusing on real-virtual synchronization applications through BIM and DT. The results indicate that BIM applications are widely used in the AEC industry, but the development of the DT is still in its infancy. BIM has a significant potential to increase interoperability with components from the DT. This study presents a comprehensive summary of the current state of BIM and DT concepts and contributes as a basis for future research in the AEC industry.

Keywords: *architecture, engineering, and construction (AEC) industry, building information modeling (BIM), digital twin (DT), innovation, technology.*

Introduction

Synchronization is to ensure that the virtual representation more closely matches the real world and/or to ensure that the real world more closely matches the virtual representation of the desired situation (Olcott & Mullen, 2020). Synchronization requires a two-way exchange of information through which the digital asset acquires data with respect to the current and previous states of the physical asset (Jones et al., 2020; Evangelou et al., 2022). From the perspective of the innovative development of the Architecture, Engineering, and Construction (AEC) industry, it is important to specify how Building Information Modeling (BIM) and Digital Twin (DT) achieve real-virtual synchronization. Hence, this study aims to review real-virtual synchronization through BIM and DT in the AEC industry.

This study is organized as follows. The second part provides an overview of BIM and DT in the AEC industry by defining BIM and DT concepts. The third part presents the research methodology. The main results and discussions are given in the fourth part. Finally, it concludes with future prospects.

An Overview of BIM and DT in the AEC industry

The integration of BIM for the AEC industry is a significant innovation in the digitalization process. The term "Building Information Model" was first proposed in the early 1990s and later became widespread by being called "Building Information Modeling (BIM)" (Deng et al., 2021). A BIM model is a three-dimensional digital representation of the building. Thanks to its shareable and reliable database, BIM is also widely applied in building lifecycle management, especially in the design, construction, and operation phases in the AEC industry (Sacks et al., 2020; Deng et al., 2021). Real-time information in BIM models cannot be updated without additional data sources (Tang et al., 2019). With the interconnection of sensing devices (e.g. IoT) that can exchange information between different platforms, the integration of real-time sensing data and information of the BIM model has become possible (Tang et al., 2019). Thanks to smart devices, BIM models have been automatically updated according to real-time building status (Deng et al., 2021). The foundation of BIM and Internet of Things (IoT) integration has led to the emergence of the Digital Twin concept.

Digital Twin (DT) started with a virtual prototype used for simulation in NASA's Apollo program virtual space facility environment and emerged as the key element technology of the 4th industrial revolution with its active implementation in the manufacturing industry (Qian, 2024). The concept of DT emerged in the field of aviation and later became widespread in the industrial manufacturing sector (Leng et al., 2019). In recent years, it has received increasing attention in the AEC industry (Deng et al., 2021). When the definitions of the DT concept in the literature are examined, there are different definitions made by researchers. One of the frequently used definitions of a digital twin in the literature is NASA's definition of "*a virtual representation of a physical object or process that serves as its real-time digital counterpart*" (Barricelli et al., 2019). According to Scleich et al. (2017), DT is identified as "*in the most general sense, a digital copy of a physical object, process or service*" (Scleich et al., 2017). Rossi (2017) explains DT as "*the mapping of a physical entity to a digital platform*" (Rossi, 2017). Furthermore, Madni et al. (2019) extended the term to the Operations and Maintenance (O&M) process by defining DTs as "*a virtual instance of a physical system (twin) that is continuously updated with performance, maintenance, and health status data of the physical system throughout the lifecycle of the physical system*" (Madni et al., 2019). Olcott and Mullen (2020) defined it as "*a virtual representation of real-world entities and processes synchronized with a certain frequency and accuracy*" (Olcott & Mullen, 2020). Jiang et al. explained DT as "*An integrated system that can detect, monitor, synchronize, simulate, calculate and test the behavior of a physical system in real-time*" (Jiang et al., 2021). Kwon and Ro (2022) defined a DT as "*information representing the characteristics and behavior of a physical entity for copying a physical entity in the digital world*" (Kwon & Ro, 2022).

DT technology is necessary to enable the combination of virtual-real, cyber-physical systems (Liu et al., 2021). DT combines artificial intelligence, sensor and IoT technologies, and transfers real-time data to the digital models (Scleich et al., 2017). The concept of a DT has an information structure consisting of a real entity (physical entity), its identical digital representation, a virtual entity (digital entity), and the data link between them (Figure 1).

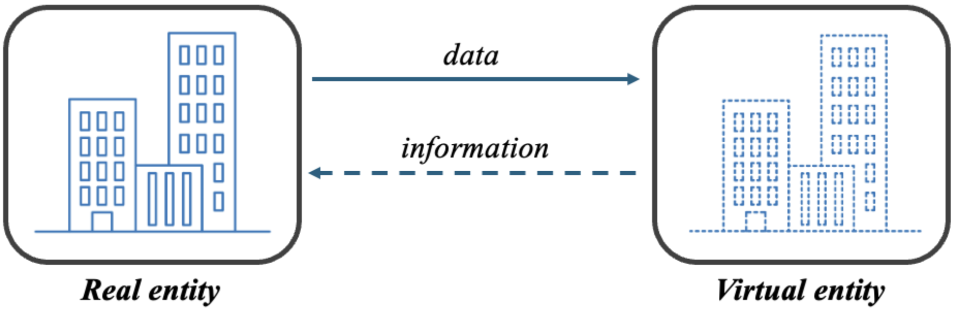

Figure 1: Schematic illustration of digital twin concept.

DTs provide the synchronization of states between the real entity and the virtual entity (Leng et al., 2019). Important considerations in DT synchronization are identifying when and how often synchronization occurs and what kind of data is synchronized (Davila Delgado & Oyadele, 2021). In the AEC industry, the first generation of DTs was used following the integration of real-time sensing data with BIM (Naderi & Shojaei, 2023). A virtual model simply represents a three-dimensional model of a structure. However, the DT must have figures and data that exist in the physical world (Deng et al., 2021). In addition, the DT performs automatic transfer of data in synchronization with the physical model (Mertala-Lindsay & Strålman, 2021).

BIM processes and DT strategies are built on a set of common principles; the improvement of process visibility, the alignment of stakeholders, and supporting planning (Sacks et al., 2020; Broo & Schooling, 2021; Davila Delgado & Oyedele, 2021). Unlike BIM, in DTs, there is a bidirectional data flow between physical and cyberspace (Grieves, 2016; Jiang et al., 2021).

Research Methodology

In this study, a literature review was carried out on real-virtual synchronization through BIM and DT. Examining the scientific literature is important in terms of explaining the research topic and presenting it understandably. As a result of the literature search, scientific studies that conducted case studies were selected to unveil how real-virtual synchronization occurs in BIM and DT. Following that, content analysis was performed to examine in detail selected studies. Content analysis is a research technique used to explore themes in-depth (Krippendorff, 1980).

The Scopus database was used for reviewing BIM and DT literature. When the Scopus database was examined, 993 scientific studies were found in the field of "BIM" and "DT" between 2017 and 2024 (Figure 2). Of these scientific studies, 677 studies were conducted in the "Engineering" research field. The field in which "BIM " and "DT " issues were most discussed in scientific studies was "Engineering". Within the scope of this study, studies dealing with real-virtual synchronization through BIM and DT in the AEC industry are examined. Totally 34 scientific studies conducted between 2020-2024 were determined in the Scopus database using the keywords "BIM", "Digital twin", and "Synchronization". Studies conducted in different disciplines outside the AEC field that did not include case studies were excluded. Finally, 11 scientific studies presented in Table 1 were included in the content analysis.

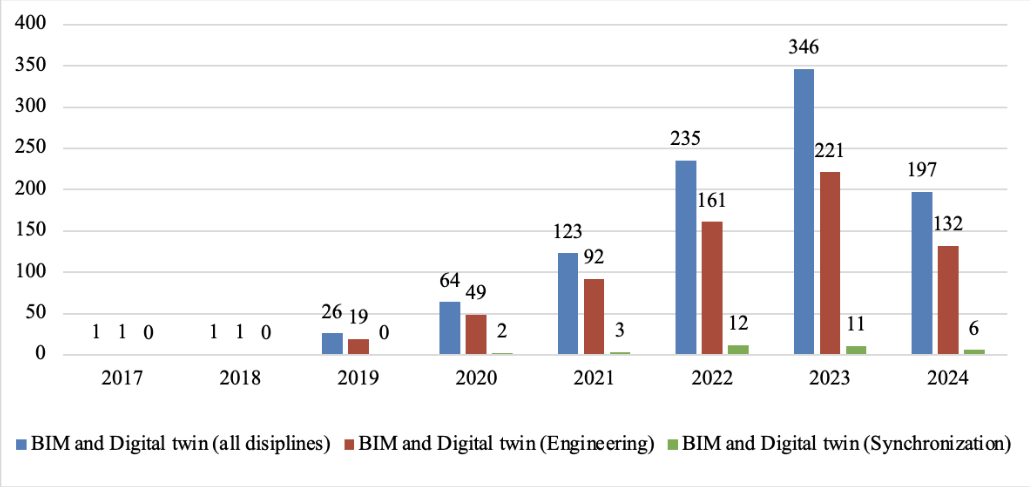

Figure 2: Studies conducted in the fields of "BIM", "Digital twin" and "Synchronization" between 2017-2024 in the Scopus database.

Results and Discussion

As shown in Table 1, 11 scientific studies were reviewed in detail according to the methods/tools used to ensure synchronization between the real entity, virtual entity, and real-virtual entity that constitute the digital twin concept. It is realized that a DT is created using the BIM model as physical assets and virtual assets. Although the scale and scope of the real asset discussed in these studies examined vary, BIM models have been created at appropriate dimensions to the scope of the virtual asset in all of them. Different methods or tools are used to achieve real-virtual synchronization, depending on the scope and purpose of the case studies. Therefore, the methods/tools used in data synchronization between the real and virtual entities considered in the digital twin concept were determined in this study.

Table 2 presents methods/tools used to achieve real-virtual synchronization in the 11 studies. Considering the studies examined in this study; To achieve real-virtual synchronization, one-way (virtual entity to real entity), two-way (real entity to virtual entity, virtual entity to real entity), and real-time synchronization methods are used (Sharma et al., 2022; Wu et al., 2022; Qian et al., 2024). In some case studies, the focus is on synchronization tools rather than the method of achieving real-virtual synchronization. In the synchronization between real and virtual entities, sensors are used to obtain temperature, CO_2 level, noise, humidity, and movement data (Grübel et al., 2022), power consumption (Evangelou et al., 2022), energy, water usage, and building occupancy rate (Boje et al., 2023), CO and NO_2 levels, temperature, visibility, risk and condition data (Biswas et al., 2023). Geographic Information Systems (GIS) are also used in data synchronization between real and virtual assets (Biswas et al., 2023). In the case study conducted by Li et al. in 2024, data used in real-virtual synchronization was collected using automatic IoT sensors (such as cameras, strain gauges, and water level meters), convergence sensors, and wired sensors (Li et al., 2024). In addition, in the study of Elghaish and his colleagues, the blockchain network was used to obtain data (Elghaish et al., 2022). Furthermore, perception robots, geological radar, total station, computer vision-based tunnel face geological survey terminals (Li et al., 2024), game engines (Jin et al., 2024), and point cloud (Gao et al., 2024) synchronization tools are used to gather data.

Table 1. Components of digital twin in the selected studies.

Source	Real entity	Virtual entity	Synchronization method/tools
Sharma et al., 2022.	Case 1- Institute for Manufacturing (IfM) building in West Cambridge Case 2- Pergenova viaduct in Genoa Case 3- Mater Private Hospital in Dublin	Case 1-Digital model Case 2-3D and 4D BIM model Case 3-3D and 4D BIM model	Case 1- real-time synchronization (data collection from IoT, RFID, sensors, WiFi environment) Case 2-one way synchronization (virtual entity to real entity) Case 3-two way synchronization (to the DT after assessment, to the Physical Asset after testing scenarios in DT)
Wu et al., 2022.	Construction site	4D BIM model	Real-time tracking, hazard identification, and visualisation
Elghaish et al., 2022.	Hospital project	4D and 5D BIM model	Recording/invoke transactions safely and automatically with blockchain network
Grübel et al., 2022.	Eight floor office building at ETH Zürich (ETHZ)	BIM model	390 sensors used to collect data of temperature, CO2-levels, noise, humidity, and motion
Evangelou et al., 2022.	Two floor smart building	BIM model	Use of sensors to monitor power consumption in the building
Boje et al., 2023.	Office building	BIM model	Monitoring data related to the energy, water usage and occupancy
Biswas et al., 2023.	Pilot project 1- Tunnel Pilot project 2- Bridge Pilot project 3- Road	Pilot project 1-BIM model Pilot project 2-BIM model Pilot project 3-BIM model	Pilot project 1-Data was provided from sensors (CO, NO2, temperature, sight distance) installed in the tunnel Pilot project 2-integrate risk and condition data on bridges into the BIM model Pilot project 3-linking data from a BIM model to a GIS based Asset Management System (AMS)
Li et al., 2024.	Case 1- Line 6 subway tunnel in Shanghai Case 2- Laoying Tunnel in Yunnan Province, China Case 3- highway tunnel, named Daxiagu Tunnel in Sichuan Province, China	Case 1-no detail Case 2-BIM model Case 3-no detail	Case 1- automatic IoT sensors (such as cameras, strain gauges, water level meters) and perception robots are adopted Case 2- Data is collected through geological radar, total station, and convergence sensors Case 3- computer vision-based tunnel face geological survey terminals and wired sensors
Qian et al., 2024.	Traditional dwelling located in Wufu Town, Fujian, China	BIM model	Physical entity-side real-time data collection through sensors and virtual digital-side intelligent control.
Jin et al., 2024.	City	BIM model	Game engine
Gao et al., 2024.	Case 1- Synthetic groove Case 2- Real-world building crack	Case 1-BIM model Case 2-BIM model	Case 1- damage detection via DeepLabV3+ and synchronizing local damage on a planar surface using point clouds Case 2- damage detection via DeepLabV3+ and synchronizing local damage on a planar surface using point clouds

Table 2. Methods/tools used to achieve real-virtual synchronization.

Method/Tools	Synchronization	Explanation	Source
Synchronization method	One way synchronization	Virtual entity to real entity	Sharma et al., 2022.
	Two way synchronization	Virtual entity to real entity, real entity to virtual entity	Sharma et al., 2022.
	Real-time synchronization	To the virtual entity after assessment, to the physical entity after testing scenarios in virtual entity	Sharma et al., 2022. Wu et al., 2022. Qian et al., 2024.
Synchronization tools	Sensors	Temperature CO2, CO, NO2 Noise Humidity Motion Power consumption Energy usage Water usage Occupancy Sight distance Risk and condition data Automatic IoT sensors (such as cameras, strain gauges, water level meters) Convergence sensors Wired sensors	Grübel et al., 2022. Evangelou et al., 2022. Boje et al., 2023. Biswas et al., 2023. Li et al., 2024.
	Perception robots		Li et al., 2024.
	Geological radar		Li et al., 2024.
	Total station		Li et al., 2024.
	Computer vision-based tunnel face geological survey terminals		Li et al., 2024.
	Game engine		Jin et al., 2024.
	Point cloud	Synchronizing local damage on a planar surface	Gao et al., 2024.

By leveraging real-time data, BIM and DT allow visualizing, monitoring, and optimizing assets, processes, and resources. However, in achieving real-virtual synchronization of BIM and DT technologies, different methods or tools must be integrated in obtaining and sharing data. The review results of 11 studies depict that one-way, two-way, and real-time synchronization methods are adopted in BIM and DT applications. The most used synchronization method is real-time synchronization. As for tools, “sensors” are primarily used for achieving real-virtual synchronization (Grübel et al., 2022; Evangelou et al., 2022; Boje et al., 2023; Biswas et al., 2023; Li et al., 2024).

Conclusions and Future Prospects

This study reviewed real-virtual synchronization through BIM and DT in the AEC industry. In recent years, DTs for information sharing, simulations, and collaborative decision-making processes are among the important trends to meet new management demands in the AEC industry. However, real-time insights are needed to continuously improve and adapt the project once it is up and running. This is where DTs become extremely useful. The recent development of DT synchronized with the IoT offers new opportunities for real-time information collection, timely data access, and efficient collaboration and coordination among stakeholders. The use of DTs allows processes to be planned more effectively, with abundant data generated about possible performance outcomes. This leads to insights that will help make necessary improvements before the end of the construction process or throughout the occupancy process. As technology and research advances, the future of DTs becomes almost limitless. As a result, DTs learn new skills and abilities day by day. Nevertheless, the DT concept in the AEC industry is still in its infancy. The research results indicate that BIM has significant potential to increase interoperability with components from the DT. More scientific studies and applications are needed to gain better insights into real-virtual synchronization through BIM and DT in the AEC industry.

References

Barricelli, B. R., Casiraghi, E., & Fogli, D. (2019). A survey on digital twin: definitions, characteristics, applications, and design implications. *IEEE (Institute of Electrical and Electronics Engineers) Access, 7,* 167653–167671.

Biswas, S., Wrighta, A., Prousta, J., Andriejauskasa, T., Geemb, C. V., Kokotc, D., Antunesd, A., Marecosd, V., Barateirod, J., Bhusarie, S., & Petrović, J. (2023). Demonstrating efficiency through data connectivity between asset management systems and IM. *Transportation Research Procedia, 72,* 1326–1333.

Boje, C., Hahn Menacho, A. J., Marvuglia, A., Benetto, E., Kubicki, S., Schaubroeck, T., & Gutiérrez, T. N. (2023). A framework using BIM and digital twins in facilitating LCSA for buildings. *Journal of Building Engineering, 76,* 107232.

Broo, D. G., & Schooling, J. (2021). Digital twins in infrastructure: definitions, current practices, challenges and strategies. *International Journal of Construction Management,* https://doi.org/10.1080/15623599.2021.1966980.

Davila Delgado, J. M., & Oyedele, L. (2021). Digital twins for the built environment: Learning from conceptual and process models in manufacturing. *Advanced Engineering Informatics, 49,* 101332.

Deng, M., Menassa, C. C., & Kamat, V. R., (2021). From BIM to DTs: A systematic review of the evolution of intelligent building representations in the AEC-FM industry. *Journal of Information Technology in Construction (ITcon), 26*(5), 58-83.

Elghaish, F., Rahimian, F. P., Hosseini, M. R., Edwards, D., & Shelbourn, M. (2022). Financial management of construction projects: Hyperledger fabric and chaincode solutions. *Automation in Construction, 137,* 104185.

Evangelou, T., Gkeli, M., & Potsiou, C. (2022). Building digital twins for smart cities: A case study in Greece. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 10(4/W2-2022),* 61–68.

Gao, Y., Li, H., Fu, W., Chai, C., & Su, T. (2024). Damage volumetric assessment and digital twin synchronization based on LiDAR point clouds. *Automation in Construction, 157 (2024), 105168.*

Grieves, M. (2016). *Origins of the Digital Twin Concept.* https://www.researchgate.net/publication/307509727_Origins_of_the_Digital_Twin_Concept.

Grübel, J., Thrash, J., Aguilar, L., Gath-Morad, M., Hélal, D., Sumner, R. W., Hölscher, C., & Schinazi, V. R. (2022). Dense indoor sensor networks: Towards passively sensing human presence with LoRaWAN. *Pervasive and Mobile Computing, 84,* 101640.

Jiang, F., Ma, L., Broyd, T., & Chen, K. (2021). Digital twin and its implementations in the civil engineering sector. *Automation in Construction, 130,* 103838.

Jin, C., Lee, Y., Lee, S., & Hyun, C. (2024). Lightweighting process of digital twin information models for smart city services. *KSCE Journal of Civil Engineering, 28,* 1304–1320.

Jones, D., Snider, C., Nassehi, A., Yon, J., & Hicks, B. (2020). Characterising the digital twin: A systematic literature review. *CIRP Journal of Manufacturing Science and Technology, 29,* 36–52.

Krippendorff, K. (1980). *Content analysis: An introduction to is methodology*, Sage, Beverly Hills.

Kwon, T., & Ro, K. (2022). A study on digital twin module design supporting modeling and synchronization. *2022 IEEE International Conference on Consumer Electronics-Asia (ICCE-Asia), Yeosu, Korea, Republic of*, pp. 1-4.

Leng, J., Zhang, H., Yan, D., Liu, Q., Chen, X., & Zhang, D. (2019). Digital twin-driven manufacturing cyber-physical system for parallel controlling of smart workshop. *Journal of Ambient Intelligence and Humanized Computing, 10,* 1155–1166.

Li, T., Rui, Y., Zhao, S., Zhanga, Y., Zhu, H., & Li, X. (2024). A quantitative digital twin maturity model for underground infrastructure based on D-ANP. *Tunnelling and Underground Space Technology, 146,* 105612.

Liu, S., Bao, J., Lu, Y., Li, J., Lu, S., & Sun, X. (2021). Digital twin modeling method based on biomimicry for machining aerospace components. *Journal of Manufacturing Systems, 58,* 180–195.

Madni, A. M., Madni, C. C., & Lucero, S. D. (2019). Leveraging digital twin technology in model-based systems engineering. *Systems, 7*(1), 7.

Mertala-Lindsay, T., & Strålman, J. (2021). Construction digital twin: From early design to project delivery. *Master Thesis, Chalmers University of Technology,* Gothenburg, Sweden.

Naderi, H., & Shojaei, A. (2023). Digital twinning of civil infrastructures: Current state of model architectures, interoperability solutions, and future prospects. *Automation in Construction, 149,* 104785.

Olcott, S., & Mullen, C. (2020). *Digital twin consortium defines digital twin.* https://www.digitaltwinconsortium.org/2020/12/digital-twin-consortium-defines-digital-twin/.

Qian, Y., Leng, J., Zhou, K., & Liu, Y. (2024). How to measure and control indoor air quality based on intelligent digital twin platforms: A case study in China. *Building and Environment, 253,* 111349.

Rossi, B. (2017). *Digital twinning explained*. https://www.raconteur.net/business-innovation/digital-twinning-explained.

Sacks, R., Brilakis, I., Pikas, E., Xie, H. S., & Girolami, M. (2020). Construction with digital twin information systems, *Data-Centric Engineering*, *1* (6), https://doi.org/10.1017/dce.2020.16.

Scleich, B., Anwer, N., Mathieu, L., & Wartzack, S. (2017). Shaping the digital twin for design and production engineering. *CIRP Annals - Manufacturing Technology*, *66*, 141–144.

Sharma, A., Kosasih, E., Zhang, J., Brintrup, A., & Calinescu, A. (2022). Digital twins: State of the art theory and practice, challenges, and open research questions. *Journal of Industrial Information Integration*, *30*, 100383.

Tang, S., Sheldena, D. R., Eastmana, C. M., Pishdad-Bozorgib, P., & Gaob, X. (2019). A review of building information modeling (BIM) and the internet of things (IoT) devices integration: Present status and future trends. *Automation in Construction*, *101*, 127–139.

Wu, S., Hou, L., Zhang, G., & Chen, H. (2022). Real-time mixed reality-based visual warning for construction workforce safety. *Automation in Construction*, *139*, 104252.

Building Information Modeling (BIM)-Based On-Site 3D Printer Position Optimization and Path Planning for Digital Fabrication

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Abstract

The on-site integration of 3D printing and Building Information Modeling (BIM) has shown the potential to improve the production processes of digital fabrication with concrete. BIM can be used in the site planning and optimization of the digital fabrication process by optimally positioning the 3D printers on the construction site. In this work, a BIM-based 3D-printer position optimization and path planning tool was developed using the Dynamo plugin of the Autodesk Revit software. This tool works similarly to the BIM-based site layout optimization tools for the operation and positioning of major construction equipment (e.g., cranes). The developed tool considers the physical properties of a robotic arm 3D printer, such as its dimensions and printing range, as well as the geometry and location of the elements to be printed on-site. It suggests the optimum path for the 3D printer to fabricate a project. The position optimization and path planning tool is validated for a case study of a real-world 3D-printed single-floor office building, and successfully reduced the number of steps required for printing the walls of the case study building, enabling significant time and energy savings.

Keywords: *additive manufacturing, building information modeling, digital fabrication, 3D printing, site layout optimization*

Introduction

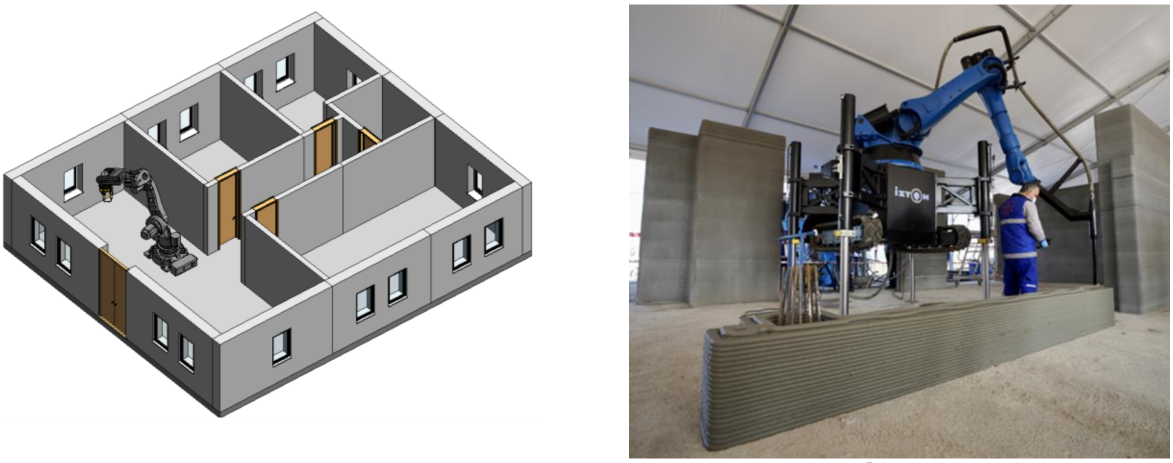
There has been an increase in the number of Building Information Modeling (BIM) and Additive Manufacturing (AM) applications in the construction industry over the last decade. There is great potential in integrating BIM and AM to increase the efficiency of construction processes. BIM is the digital representation of a facility's physical and functional characteristics, and it is used to store and manage all the information generated throughout the project's life cycle (Eastman et al., 2011). BIM applications in construction projects provide crucial information related to the life cycle of projects and enable visualization of the design and construction of building elements or simulations based on the performance and physical properties of buildings (He et al., 2021). One of the main uses of BIM is to plan the operation stages of a construction project well before the project starts. It has been proven to be a powerful tool for the optimization and planning of the site layout based on the characteristics of sites (Amiri et al., 2017) and the location of large equipment (e.g., tower cranes) (Vermeulen, 2019). A recent example of cranes, for instance, includes BIM-based visualization and optimization applications for crane positioning and planning of crane lifting activities during construction (Hu et al., 2021). Site layout optimization aims to decrease project costs while increasing productivity and safety of working conditions (Sadeghpour & Andayesh, 2015). BIM-based applications can help identify the optimal construction site layouts by creating realistic models that provide spatial data, dynamic navigation, and a continuous understanding of the indoor and outdoor spaces (Zavari et al., 2022).

Integration of BIM with AM has the potential to provide better workflows and efficient planning for the 3D printing processes on construction sites (Olsson et al., 2021; Garcia-Alvarado et al. 2022). Earlier, BIM and AM integration was envisioned for producing large-scale building projects with 3D printers, as well as life cycle assessments of printed construction products/projects (Wu et al, 2016). More recently, researchers have been investigating the use of BIM for 3D printing of concrete with robotic systems (Garcia-Alvarado et al., 2022, Anane et al., 2023), and looking at the feasibility and economic analysis of integrating BIM and AM while pointing out the gaps between BIM applications and 3D printing in the construction industry (Koroteev et al., 2022). For AM applications, detailed information such as the performance of the materials, spatial relationships of system and project elements, or manufacturing information can be obtained from BIM rather than just the geometry information (Shou et al., 2015). By bringing together AM and BIM applications, designers can change the design of the building or design of the printable elements during different stages of the project, or operators can analyze the building's printability and constructability before initiating the printing process (Wu et al., 2016). BIM can also assist in the visualization of the construction project and the worksite and in planning and optimizing the 3D printing workflow. Although BIM has been significantly used in the computerized design and off-site prefabrication of industrial elements, the relationship between BIM and AM regarding the detailed modeling, designing, and 3D printing processes of projects has not been investigated (He et al., 2021).

To further explore the integration of BIM and AM for on-site digital fabrication applications, this study developed a BIM-based tool for optimizing the position of robotic arm 3D printer systems on a construction site for digitally fabricated projects. This tool is used to determine the optimum positioning of a 3D printer at a construction site and provide an optimum working plan for the 3D printer. The goal of this tool is to enable the printing operation of all printable building elements to be completed through an optimized operation scenario. To the authors' knowledge, this study is the first BIM-based optimization and automated path planning study to position robotic arm 3D printers for digitally fabricated construction projects.

Methodology

A real-world 3D-printed construction project was used as a case study in this research for the development of the BIM-based optimization and automated path planning tool. The case study building is a single-story office building (Fig. 1a) that was printed with a KUKA robotic arm 3D printer by ISTON Corporation A.S. in Istanbul, Turkey, in 2021 (Fig. 1b). Information related to the case study building project, such as the two-dimensional (2D) floor plans, the schedule and progress reports were obtained. The 3D-printed case study building is approximately 150 m^2 and consists of 20 unique 3D-printed walls, 3m in height and at lengths ranging between 3 to 5 m. During the construction of the case study building, the project engineers determined 20 different points in the front and mid-points of each wall for positioning the robotic arm 3D printer for printing each and every element. The printing process was completed in 20 steps by placing the robotic arm printer at these points individually for each wall. All the printing process was completed in 20 workdays by working 8 hours a day. Through using the developed BIM-based optimization and path planning tool, this study aimed to demonstrate: (1) the 3D printing process of the case study building can be optimized by decreasing the number of times the printer needs to be carried from one location to another during the construction, and therefore, (2) the efficiency of the printing process can be improved by saving time and energy.



(a) (b)

Figure 1: (a) A 3D view of the 3D-printed single-story office building in Revit, and (b) a close-up of the KUKA robotic arm 3D printer (ISTON).

Based on the obtained 2D floor plans, the BIM of the case study building was modeled in Autodesk Revit (version 20.0.0.377) (Fig. 1a). This was followed by the coding of the position optimization and path planning tool using Revit's visual programming plug-in Dynamo (version 2.1.1.7733). With its open-source, built-in node library, Dynamo enables industry professionals to perform design optimization, apply certain functions on lists of building elements, and model additional elements outside of Revit (Autodesk 2019, Wang et al., 2022). The development process consists of three main steps as demonstrated in Fig. 2: (1) determining the possible points for placing the printer within the project boundaries, (2) finding how many times the printer needs to be relocated for completing all the printing in the project, and lastly, (3) determining the most effective route for the 3D printer considering the distances between the relocating points determined in the previous step. This third step also considers the properties of the concrete mix and the effects of material properties on the thermal insulation of the walls if needed.

Implementation Details

Step 1: In this step, all available locations for placing the robotic arm 3D printer on site are determined by checking for interference between the element surfaces of the project in BIM and all points, and also by checking for clashes between the project's walls and the printer's footprint. The slab area is divided into a virtual grid to obtain points on the project surface where the printer could be located. A certain number of points are created based on the sizing of the grid (e.g., 100 points for a 10 x 10 grid). The possible printer locations are the ones that are confirmed to have no interference between the printer and the building elements to be printed, and this is determined by considering the dimensions of the printer. By combining several built-in Dynamo nodes and newly coded Python scripts, all possible points in the project where the printer can be placed are determined (Figure 3).

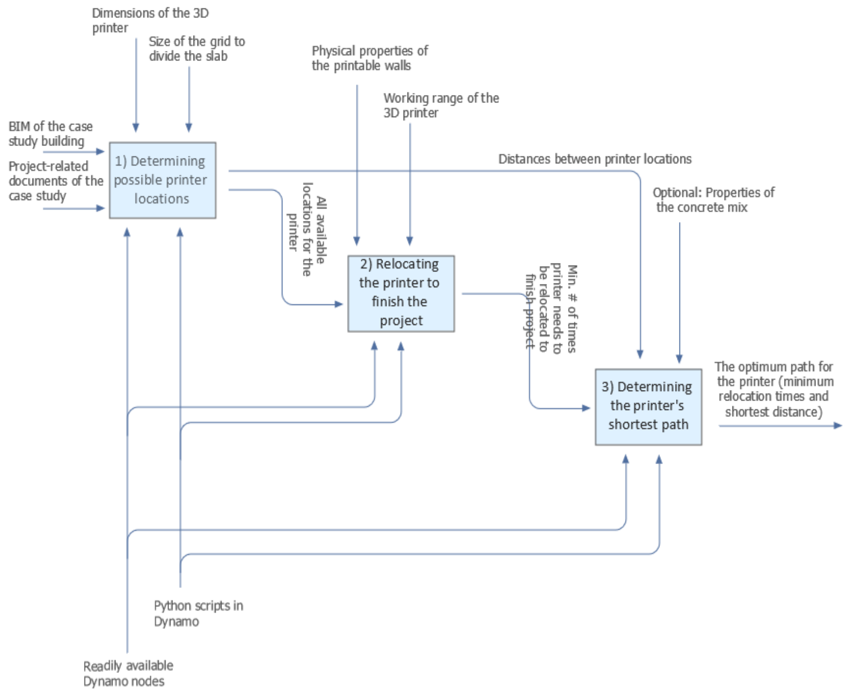


Figure 2: The main steps for BIM-based site layout optimization for robotic arm 3D printers.

Step 2: In this step, the minimum number of repositioning for the printer is calculated by (1) identifying which wall can be printed from which point, (2) creating a list of printable wall IDs from the possible points and followed by (3) assigning scores based on how many walls can be printed at a point. Finally, the optimization algorithm is used for finding the minimum number of printer repositioning that is needed. This step detects the locations where the printer can print more than one wall to avoid the need for moving the printer to a different point each time a wall is printed (i.e., 20 different printing points for each of the 20 walls in the case study project). The printability of every wall is evaluated from every single point on the project and the working range of the robotic arm 3D printer and the properties of the walls, such as wall dimensions, are considered.

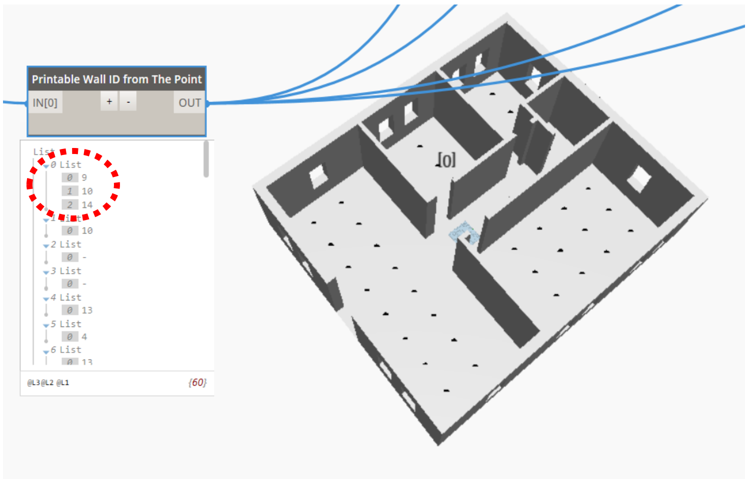


Figure 3: Dynamo script to identify which walls can be printed at each point: Walls 9, 10, and 14 of the building can be printed when the printer is positioned at Point 0.

Step 3: Based on the distances between the determined relocation points on the slab, this step uses the previously determined printer locations to calculate the shortest path for the printer to travel. Also, in this step, the user can incorporate the properties of the concrete mix into the sequencing of the printing process if needed. When the concrete mix has a short setting time, the user might want to ensure the proper thermal insulation of the project by printing adjacent exterior walls simultaneously.

Results and Discussions

The results of the optimization for the case study: The results for the case study building are obtained based on the 32x32 optimum grid sizing assigned by the developed tool by taking into account the dimensions of the working area for the printer, the printable walls and the printer's working range (Fig. 4). As a result of this division, 1024 points were initially created in the working area. Then, the intersection check nodes found 221 of these 1024 points were intersecting with the printable wall surfaces over the slab and eliminated these while leaving 803 points to work with. The other intersection check found that 309 of the remaining 803 points were not available for locating the printer since the footprint of the printer over these points was clashing with the walls. Then, these clashing points were eliminated, and 494 potential points remained in the project area. According to these 494 available final points, the optimization tool determined seven printing points for the 20 walls in the project as demonstrated in Fig. 4 whereas the printer had to be moved 20 times to 20 different printer locations to complete the project in the real-world printing process of the case study building.

Applicability to other projects: This tool can be applied to optimize the printing process in other digitally fabricated construction projects for different designs, walls, and project areas. One of the parameters in the developed algorithm that will change from project to project is the sizing of the grid that will divide the slab to assign points on the project area in Revit. This is based on the size of the project area and the dimension of the 3D printer that is used in a given project. This step is crucial in finding the minimum number of steps for the relocation of the robotic arm 3D printer during the printing process for any given project. The sizing of the grid is calculated based on three parameters: (1) the working diameter of the robotic arm of the printer (i.e., max. reaching distance), (2) the maximum length of the printable walls, and (3) the distance between the printer and the walls. A printer is envisioned to be located in the middle point of a wall, and the difference between the working radius of the robotic arm and half of the wall length is used to determine the minimum division number. Based on the dimensions of the working area and the printer, the algorithm divided the project area with a 32x32 grid to provide the optimum number of possible printer locations (1024 points) to initiate the process.

Incorporating the concrete mix properties: The developed optimization tool can incorporate the properties of different concrete mixes if needed. To demonstrate this, another printing scenario was applied to the case study project. The goal was to ensure efficient thermal insulation was achieved in the neighboring exterior walls on the project area's corners. In this case, the corner exterior walls will be printed at the same time, and therefore, the gaps between asynchronously set walls will be eliminated. In this scenario, the printable walls were separated into two groups, exterior and interior walls, and the printing process of the walls was envisioned to be completed in two stages. First, the exterior walls were taken as a group and printed, and then the interior walls were taken as another group and printed. For this scenario, since the working area of the printer did not change, the division number of the slab remained the same. The project has 11 exterior walls, and eight of them are located at the corner points (Fig. 1a). Every two walls located at the four different corners of the project are printed as monoliths to provide efficient insulation. The algorithm determined seven points to locate the printer to print the 11 exterior walls (i.e. Point 669, Point 524, Point 478, Point 33, Point 681, Point 660, and Point 584). Next, the interior walls were examined as a second group regardless of their insulation property, unlike the exterior walls. For the remaining nine walls, the algorithm determined four different points (i.e. Point 616, Point 626, Point 608, and Point 633) and the entire project was able to be printed in 11 steps. When the setting properties of the concrete mix were considered, the optimization algorithm was able to decrease the number of times the printer needed to be relocated from 20 to 11.

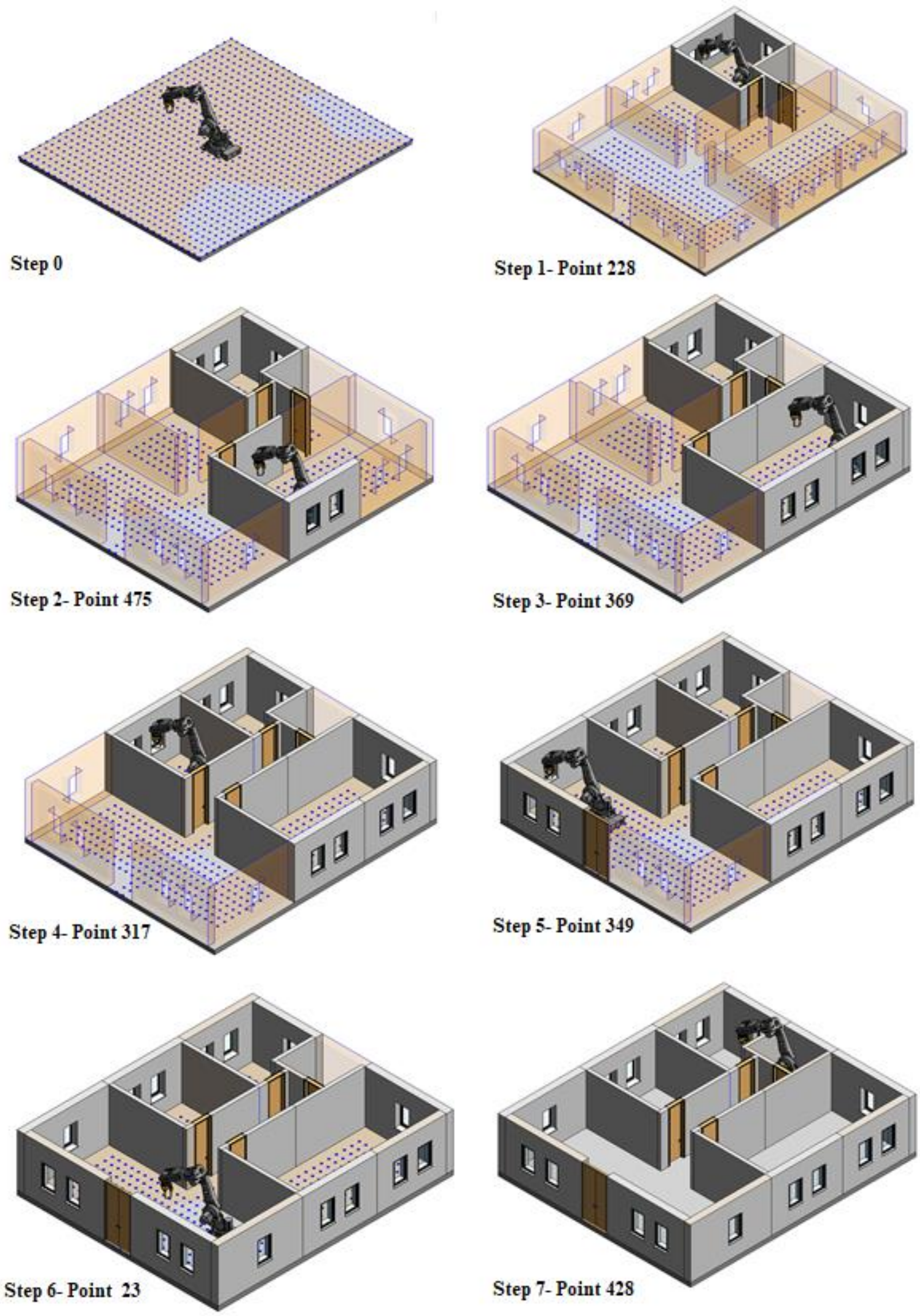


Figure 4: The optimum printing sequence of the case study project in seven steps determined by the developed BIM-based optimization tool.

Verification of the developed algorithm: To verify that the developed algorithm can effectively determine the sizing of the invisible grid applied on the project area, different grid sizes are evaluated by manually changing the grid size. For dividing the slab, several alternative grid sizes were tested, such as 35x35, 40x40, 50x50, 60x60, 70x70, 80x80, 90x90, and 100x100. It was observed that while the size of the grid was going up to 100 from 32, the minimum number of times the printer needed to be relocated remained the same, and seven new locations were determined according to the new possible points in each test. This was tested with numbers smaller than 32 and the results required the printer to be relocated were more than seven times for completing all the walls. Therefore, this test demonstrated that the sizing of the grid assigned by the algorithm gives the minimum number of times the printer needs to be relocated.

Conclusions

This study proposes a BIM-based automated position optimization and path planning tool for robotic arm 3D printers for on-site 3D printing applications. This tool automatically determines the minimum number of position changes for the printer during construction and, therefore, aims to bring time and energy savings in digitally fabricated construction projects. Considering the design of a project and certain project characteristics, the goal is to determine the positions where a robotic arm 3D printer could be located on a job site while keeping at a minimum the number of times the printer will be relocated. This tool is applied to a single-story office building case study. The construction of this case study building represents a typical 3D printing process for single-floor buildings in which the on-site planning of the 3D printing process is usually done intuitively by the project engineers. While in the real-world application, the case study building was completed by relocating the printer 20 times to 20 different points around the project area, this study optimized the printing process by relocating the printer only 7 times to 7 different locations. This result demonstrates that there were 13 unnecessary relocation steps for the robotic arm 3D printer to print some of the walls in the project, which corresponds to a 65%-time savings for the actual project. This finding is promising as it ensures energy savings and time efficiency in the field operations of robotic arm 3D printers.

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References

Amiri, R., Sardroud, J. M., & Soto, B. G. de. (2017). BIM-based Applications of Metaheuristic Algorithms to Support the Decision-making Process: Uses in the Planning of Construction Site Layout. *Procedia Engineering*, 196, 558–564.

Anane, W., Iordanova, I., & Ouellet-Plamondon, C. (2023). The Use of BIM for Robotic 3D Concrete Printing. In *Canadian Society of Civil Engineering Annual Conference*, 325-336.

Autodesk, (2019). “The Dynamo Primer” accessed 2019, <https://primer.dynamobim.org/>
COBOD. “*Gantry VS. Robotic Arm*”, https://cobod.com/products/bod2/gantry-vs-robotic-arm/

Eastman, C. M., Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2011). *BIM handbook: A guide to building information modeling for owners, managers, designers, engineers, and contractors*. John Wiley & Sons.

García-Alvarado, R., Moroni-Orellana, G., & Banda, P. (2022). Development of Variable Residential Buildings with 3D-printed Walls. *Buildings*, 12(11), 1796.

He, R., Li, M., Gan, V. J. L., & Ma, J. (2021). BIM-enabled computerized design and digital fabrication of industrialized buildings: A case study. *Journal of Cleaner Production*, 278.

Hu, S., Fang, Y., & Bai, Y. (2021). Automation and optimization in crane lift planning: A critical review. *Advanced Engineering Informatics*, 49, 101346.

ISTON. “3D Beton Yazıcı Teknolojsi”, <https://iston.istanbul/3d-beton-yazici-teknolojisi>.

Koroteev, D. D., Huang, J., & Koreneva, A. I. (2022). Cost analysis of the combined application of 3D-printing and BIM technologies in the construction industry. In *AIP Conference Proceedings*, 2559.

Olsson, N. O., Arica, E., Woods, R., & Madrid, J. A. (2021). Industry 4.0 in a project context: Introducing 3D printing in construction projects. *Project Leadership and Society*, 2, 100033.

Sadeghpour, F., & Andayesh, M. (2015). The constructs of site layout modeling: an overview. *Canadian journal of civil engineering*, 42(3), 199-212.

Shou, W., Wang, J., Wang, X., & Chong, H. Y. (2015). A comparative review of building information modeling implementation in building and infrastructure industries. *Archives of computational methods in engineering*, 22(2), 291-308.

Vermeulen, D. (2019), Construction Dynam(o)ite: Explode Productivity with Dynamo, accessed 16 09 2019, https://medium.com/autodesk-university/construction-dynam-o-ite-explode-productivity-with-dynamo-db1d5d609fb0

Wang, Y. G., He, X. J., He, J., & Fan, C. (2022). Virtual trial assembly of steel structure based on BIM platform. *Automation in Construction*, 141, 104395.

Wu, P., Wang, J., & Wang, X. (2016). A critical review of the use of 3-D printing in the construction industry. *Automation in Construction*, 68, 21-31.

Zavari, M., Shahhosseini, V., Ardeshir, A., & Sebt, M. H. (2022). Multi-objective optimization of dynamic construction site layout using BIM and GIS. *Journal of Building Engineering*, 52, 104518.

Horizons of 5IR in AEC: A Focus on Digital Twins and Circular Economy

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Abstract

Since the turn of the millennium, digital technologies have become ubiquitous in daily life, marking the advent of the fourth industrial revolution (4IR), which has now evolved into the fifth Industrial Revolution (5IR). The key distinction between 4IR and 5IR lies in 5IR's emphasis on human-technology collaboration and environmental considerations. These revolutions have also impacted the architecture, engineering, and construction (AEC) sector, where various technologies, including digital twins (DT), are employed. DT, an emerging technology facilitating interaction between physical and virtual worlds, holds promise across various fields, including AEC, although its adoption in the sector is still in its early stages. This study examines the potential of DT within AEC from the perspective of the circular economy, a trend gaining traction across different domains, including AEC. It explores how DT technology can align with circular economy principles in AEC and its significance in the context of 5IR. Through a systematic literature review and case studies, this study conceptualizes the integration of 5IR, AEC, DT, and circular economy, concluding with implications for sustainable development and smart cities, thereby laying a groundwork for future research and practices.

Keywords: *AEC, circular economy, digital twins, smart cities, sustainable development, 5IR.*

Introduction

The construction sector, contributing approximately 6% to global GDP, serves as a significant driver of economic activity across various industries, from raw material extraction to on-site construction. Over time, this sector has witnessed notable technological advancements, but it now faces pressing challenges associated with climate change and dwindling resources, underscoring the critical importance of sustainability. With the AEC sector accounting for 40% of global CO2 emissions, urgent action is imperative. Key areas for improvement include revising construction methods, enhancing efficiency, prioritizing durability, and adopting sustainable practices. By harnessing data and digital solutions, stakeholders can gain a comprehensive understanding of building lifecycles, facilitating the pursuit of climate targets in a sustainable manner. This transformative shift is observable in the sector's widespread integration of technology, ranging from design and management to actual construction activities (Nemetschek Group Blog, 2022; Musarat et al., 2023).

The pervasive influence of digital technologies has permeated nearly every aspect of daily life, heralding the onset of the fifth Industrial Revolution (5IR), characterized by human-technology collaboration, and heightened environmental consciousness. In the architecture, engineering, and construction (AEC) sector, digital technologies have led to a paradigm shift in traditional practices, offering unprecedented opportunities for efficiency, sustainability, and collaboration. At the forefront of this revolution is the concept of digital twins (DT), poised to reshape how we design, construct, and manage built environments by bridging the physical and virtual realms. Simultaneously, the principles of the circular economy have gained momentum, seeking to minimize waste, maximize resource efficiency, and promote material reuse and recycling. Within the context of 5IR, the convergence of digital twins and circular economy principles presents a unique opportunity to revolutionize the AEC sector towards a more sustainable future (Miyasaka et al., 2019; Musarat et al., 2023).

This study explores the horizons of 5IR in the AEC sector, with a focus on the intersection of digital twins and circular economy. This study marks an initial step in exploring the intersection of digital twins and circular economy principles within the Architecture, Engineering, and Construction context. While existing literature has extensively investigated these concepts in isolation, there is a scarcity of comprehensive studies that delve into their combined application within the AEC domain. Through a systematic literature review, recent advancements are examined, providing valuable insights into sustainable development, smart cities, and the future of the built environment.

5IR and AEC

Emerging from the foundations laid by the 4th Industrial Revolution (4IR), the Architectural, Engineering, and Construction (AEC) sector has witnessed a profound integration of technology, ushering in a new era of innovation and efficiency. Through the strategic deployment of sensors for environmental monitoring and the implementation of automation, 4IR has empowered the AEC industry with intelligent systems capable of autonomous decision-making and streamlined production processes. Building upon this technological groundwork, the 5th Industrial Revolution (5IR) represents a paradigm shift, emphasizing close collaboration between humans and technology (Miyasaka et al., 2019; Musarat et al., 2023).

Key rationales for embracing IR 5.0 enabling technologies in the AEC sector include harnessing Augmented Reality (AR) and Virtual Reality (VR) for inclusivity, training, and industrial testing; integrating advanced safety gear and tools to augment human skills and enhance safety protocols; deploying automatic speech and gesture detection systems to streamline communication and task execution; employing digital twins and simulations for real-time monitoring and predictive maintenance; incorporating collaborative robots (cobots) to complement human workers effectively; promoting seamless human-machine integration to bolster productivity and flexibility; offering adaptable solutions that drive down costs and space requirements; delivering user-friendly interfaces for intuitive adoption and integration; broadening the scope of automated tasks and applications; and fortifying safety protocols through advanced sensors and autonomous systems (Musarat et al., 2023). In the context of the AEC sector, this collaboration is epitomized by the concept of Construction 5.0, an innovative approach that marries cutting-edge technologies like artificial intelligence, the Internet of Things (IoT), and digital twins with human ingenuity and creativity. However, despite the immense potential of these advancements, significant challenges such as investment costs, skill development requirements, and regulatory complexities must be addressed to fully harness the benefits of 5IR in the AEC industry. By embracing these transformative changes, the AEC sector stands to gain in terms of enhanced efficiency, sustainability, and competitiveness. Moreover, the implications extend beyond mere technological integration, encompassing workforce training, managerial strategies, and avenues for future research and development (Miyasaka et al., 2019; Musarat et al., 2023).

DT and AEC

Digital twins (DT) are poised to revolutionize the Architectural, Engineering, Construction, and Facility Management (AEC/FM) industry, ushering it into the industry 4.0 era through advanced asset management solutions throughout their lifecycle. However, there is confusion surrounding the term "DT" within the AEC/FM sector, often conflated with Building Information Modeling (BIM). Unlike BIM, which enriches static 3D models with information, DT represents a dynamic concept characterized by ongoing data exchange between its digital and physical counterparts (Fjeld, 2020; Hosamo et al., 2022). The integration of digital twins enables real-time monitoring and analysis of construction projects, enhancing efficiency and facilitating informed decision-making throughout the project lifecycle. This transformative approach extends beyond construction, supporting facilities management by serving as digital replicas of built assets post-construction. DTs continue to facilitate efficient operation, maintenance, and performance monitoring, identifying opportunities for optimization and sustainability improvements through real-time data analysis and evidence-based decision-making (Miyasaka et al., 2019; Hosamo et al., 2022; Musarat et al., 2023).

As a case study of digital twins in AEC is the collaboration between Skanska, a construction company, and Houston Community College (HCC) to create a digital twin of HCC’s main campus. The digital twin can be used by prospective students to explore the campus virtually. It can also be used by HCC to train staff and simulate different scenarios (Figure 1) (Skanska USA Commercial Development, 2023).

Figure 1: Shows digital twin model of Houston Community College's main campus. (Skanska USA Commercial Development, 2023).

Circular Economy in AEC

Since the 1973 oil embargo, the architecture, engineering, and construction (AEC) sector has implemented various measures to reduce energy consumption, including enhanced building insulation. However, these measures have inadvertently increased demand for building materials, exacerbating resource scarcity and waste generation challenges. Notably, demolition accounts for a significant portion of waste in the AEC sector, prompting academic interest in the circular economy (CE) as a solution. Despite the CE's success in other industries, its implementation in the AEC sector faces hurdles, including ambiguity regarding circularity definitions and the sector's unique characteristics. Alternative approaches like sustainable building practices and design for deconstruction (DfD) show promise, but inconsistent terminology and a lack of consensus hinder adoption. While efforts to classify alternative approaches have shed light on diversity, a comprehensive examination of barriers to sustainable design remains absent in current literature. Overcoming these barriers is crucial for advancing sustainability in the AEC sector and realizing the potential of the CE paradigm (Charef et al., 2021).

Barriers to implementing the circular economy (CE) in construction have been categorized into three primary domains: disciplines (economy, environment, culture), specific stakeholders (owners, designers), and construction phases (design, in use). The construction industry's compartmentalized operational methods create obstacles by inhibiting effective communication across phases and stakeholders, presenting a significant challenge. For successful CE implementation, a comprehensive approach involving all stakeholders and asset phases is essential. The selected macro-categories, drawn from existing literature, encompass economic, sociological, political, organizational, technological, and environmental barriers, with additional subcategories addressing specific stakeholders or phases as necessary (Charef et al., 2021; Shooshtarian et al., 2023).

Ababio and Lu (2023) delve into the complexities of implementing circular economy principles in construction, grouping barriers into clusters such as framework and theory-related, political, and legislative, social, and cultural, financial, and economic, and technological barriers. They highlight that social and cultural, as well as financial and economic challenges, are particularly pronounced at the micro level, whereas technological barriers are more prominent at the meso level. Barriers at the macro level predominantly pertain to policies, regulations, and overarching frameworks. Enabling factors critical for realizing the circular economy concept include technological advancements, policy education, and awareness initiatives, as well as opportunities for financing. It's essential to acknowledge that Ababio and Lu's (2023) insights stem from an analysis of journal publications. However, potential biases inherent in the dataset sourced from Web of Science and Scopus may restrict the comprehensiveness of their findings. Furthermore, the subjective nature of scientific measurement, particularly relying solely on citation counts, may influence the interpretation of research outcomes. These factors warrant consideration when interpreting the study's findings.

A circular built environment integrates principles of a circular economy into urban systems, fostering regeneration and accessibility. This approach supports human well-being, improves natural systems, and ensures material abundance without environmental harm. Decision-making considers interactions between various components and focuses on economic, environmental, and social outcomes. Digital technologies aid asset sharing and management, making services more accessible. Urban planning aims for resilient communities with nature integrated to enhance well-being. Continuous material cycles minimize pollution and promote reuse. Buildings are designed for easy maintenance and flexibility, while integrated infrastructure systems prioritize efficient resource use (Acharya et al., 2018).

The Circular Building project serves as a case study illustrating the application of circular economy principles in construction. This project showcases a circular approach to building design and construction, focusing on intentional design for disassembly and material reuse at the end of its service life. Notably, recycled materials such as timber and steel offcuts were used during construction, demonstrating a commitment to material sustainability. The design process employed 3D modeling software to facilitate collaborative practices across the construction supply chain. Furthermore, innovative technologies such as low-voltage electrical systems and rainwater harvesting were incorporated into the project to enhance its overall resource efficiency (Figure 2) (New Civil Engineer, 2016).

Figure 2: Shows the Circular Building project. *BenBlossom* from (New Civil Engineer, 2016).

Circular Economy and Digital Twins in AEC

Digital twinning is a concept in which a virtual replica, or "twin," of a physical building or infrastructure is created. This virtual model is designed to mirror the real-world structure in terms of its characteristics, behavior, and performance. The potential of digital twinning lies in its ability to support various stages of a building's life cycle. By providing a digital representation that closely resembles the physical building, stakeholders can assess and plan for different scenarios and outcomes. This includes considering factors such as maintenance, renovations, and even end-of-life considerations (Koutamanis, 2024).

Despite its promising potential, implementing digital twinning in practice may encounter challenges. These challenges could include technical complexities, logistical issues, or difficulties in acquiring and managing data effectively. Additionally, while there is significant discussion and research on digital twinning in academic and professional circles, practical case studies demonstrating its real-world application are often limited. To fully harness the benefits of digital twinning for advancing circularity in the architecture, engineering, construction, and operation (AECO) sector, a holistic approach is necessary. This involves integrating digital twinning seamlessly into existing AECO processes and workflows. Instead of treating digital twinning as an isolated or optional component, it should be considered a fundamental aspect of how projects are planned, executed, and managed (Koutamanis, 2024).

In summary, while digital twinning holds great promise for enhancing circularity in the AECO sector, its successful implementation requires addressing technical challenges and ensuring it becomes an integral part of industry practices (Koutamanis, 2024).

Results and Discussion

The integration of digital technologies within the Architecture, Engineering, and Construction (AEC) sector, driven by the fifth Industrial Revolution (5IR), presents vast opportunities for innovation and efficiency. 5IR blends human creativity with advanced digital tools. However, unlocking the full potential of 5IR in AEC necessitates overcoming challenges such as investment costs and skill development requirements. Digital twins have emerged as transformative assets in the AEC sector, enabling real-time monitoring and analysis throughout the lifecycle of built assets. Unlike traditional Building Information Modeling (BIM), DTs provide dynamic, data-driven representations for informed decision-making and optimization.

Simultaneously, the circular economy paradigm offers a holistic approach to sustainability in the AEC sector, emphasizing material reuse, waste reduction, and regenerative design principles. Despite the historical focus on energy efficiency, challenges like resource scarcity and waste generation persist. Overcoming barriers to circularity implementation, including disciplinary, stakeholder, and phase-related complexities, requires a comprehensive approach addressing economic, sociological, and technological challenges. Integrating circular economy principles with digital twins holds promise for advancing sustainability and efficiency in the built environment.

However, practical challenges in implementing digital twins, such as technical complexities and data management issues, underscore the need for a holistic approach that seamlessly integrates digital twins into industry practices. While promising, practical implementation of digital twins may encounter technical and logistical hurdles. To fully harness their benefits for circularity, seamless integration into existing AEC processes and workflows is essential. In conclusion, the convergence of digital twins and circular economy principles presents a transformative opportunity for the AEC sector. Addressing technical challenges and fostering industry-wide adoption can unlock the full potential of digital twins in advancing sustainability and efficiency in the built environment.

Conclusion

This paper has examined the transformative potential of digital twins and circular economy principles within the Architecture, Engineering, and Construction (AEC) sector, especially in the context of the fifth Industrial Revolution (5IR). It lays the groundwork for future research and practices aimed at further exploring and leveraging the synergies between digital twins and circular economy principles in the AEC sector.

Future research directions encompass exploring interdisciplinary approaches to integrate digital twins and circular economy principles with emerging technologies for enhancing resource management in construction projects. Longitudinal studies are imperative to assess the enduring impacts of digital twins and circular economy practices on sustainability performance within construction endeavors. Furthermore, delving into case studies and best practices will yield valuable insights into the effective application of digital twins and circular economy principles across varied construction contexts. It is essential to investigate strategies for stakeholder engagement and collaboration to foster sustainable practices in the construction sector. Additionally, scrutinizing the influence of policy and regulatory frameworks on incentivizing sustainable practices, particularly concerning digital twins and circular economy principles, is pivotal for guiding future advancements in the Architecture, Engineering, and Construction (AEC) domain.

By addressing these areas of research, scholars and practitioners can contribute to advancing sustainability and innovation in the AEC sector, ultimately fostering a more resilient and environmentally conscious built environment in line with the principles of the fifth Industrial Revolution.

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Declaration

The authors assert full ownership of the ideas, reference selection, research topic, and subtopics presented in this work. However, ChatGPT 3.5, an artificial intelligence tool, was employed for rephrasing and proofreading. The AI's involvement was restricted to linguistic adjustments, with all original concepts and intellectual contributions credited to the authors.

References

Ababio, B. K., & Lu, W. (2023). Barriers and enablers of circular economy in construction: A multi-system perspective towards the development of a practical framework. *Construction Management and Economics*, *41*(1), 3-21.

Acharya, D., Boyd, R., & Finch, O. (2018). From principles to practices: First steps towards a circular built environment. *ARUP*, *Ellen MacArthur Foundation*.

Ammar, A., Nassereddine, H., AbdulBaky, N., AbouKansour, A., Tannoury, J., Urban, H., & Schranz, C. (2022). Digital twins in the construction industry: A perspective of practitioners and building authority. *Frontiers in Built Environment*, *8*, 834671.

Charef, R., Morel, J. C., & Rakhshan, K. (2021). Barriers to implementing the circular economy in the construction industry: A critical review. *Sustainability*, *13*(23), 12989.

Fjeld, T. M. B. (2020). *Digital twin-Towards a joint understanding within the AEC/FM sector* (Master's Thesis, NTNU).

Hosamo, H. H., Imran, A., Cardenas-Cartagena, J., Svennevig, P. R., Svidt, K., & Nielsen, H. K. (2022). A review of the digital twin technology in the AEC-FM industry. *Advances in Civil Engineering*, *2022*.

Koutamanis, A. (2024). From building information modelling to digital twins: Digital representation for a circular economy. *A Circular Built Environment in the Digital Age* (pp. 3-20). Cham: Springer International Publishing.

Miyasaka, E. L., Fabricio, M. M., & Paoletti, I. (2019). 4th industrial revolution in Brazil: Architecture, engineering and civil construction. *arq. urb*, *25*, 1-14.

Musarat, M. A., Irfan, M., Alaloul, W. S., Maqsoom, A., & Ghufran, M. (2023). A review on the way forward in construction through industrial revolution 5.0. *Sustainability, 15*(18), 13862.

Nemetschek Group Blog. (2022). The top 7 trends for the AECO industry in 2022. Retrieved from [https://blog.nemetschek.com/en/topics-and-insights/the-top-7-trends-for-the-aeco-industry-in-2022] Accessed 15-4-2024.

New Civil Engineer. (2016, November 21). Smart materials: A circular vision. Retrieved from [https://www.newcivilengineer.com/archive/smart-materials-circular-vision-21-11-2016/] Accessed 15-4-2024.

Shooshtarian, S., Hosseini, M. R., Kocaturk, T., Arnel, T., & T. Garofano, N. (2023). Circular economy in the Australian AEC industry: Investigation of barriers and enablers. *Building Research & Information*, *51*(1), 56-68.

Skanska USA Commercial Development. (2023). Digital twins: Shaping a brighter path for construction and higher education. In *Constructive Thinking*. Retrieved from [https://www.usa.skanska.com/who-we-are/media/constructive-thinking/digital-twins-shaping-a-brighter-path-for-construction-and-higher-education/]. Accessed 15-4-2024.

A Blockchain Based Construction Material Tracing Framework

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Abstract

The efficient traceability and transparent monitoring of construction material supply chains in terms of material quality have become essential for construction and building safety and quality, in addition to the operational efficiency of the projects, considering the prolonged and complex supply processes. The advancement of technologies in recent years, like blockchain, enabled new tools to create innovative solutions to the current difficulties in managing materials' origins, movements, visibilities, logistics, inventories, and compliances. The main objective of this study is to present a blockchain based construction material tracing framework that ensures the transparent monitoring of all the suppliers and the quality, safety, and reliability of the construction material supply chains during the entire processes. The framework is designed to improve construction quality management demands with increased efficiency and credibility in the monitoring and traceability of material supply chains. The material tracing system eliminates the limitations of traditional centralized models with the help of blockchain technologies by improving the materials' accessible information and secured data flow among various stakeholders of the chains, and thus minimizing the possible problems and uncertainties that affect the quality of the materials, in addition providing convenient management and coordination of the multiple construction materials from different resources.

Keywords: *blockchain technologies, construction material supply chains, material tracing systems, quality management, transparent monitoring.*

Introduction

The supply chain processes of the construction materials significantly affect the overall success, covering both short and long terms of the construction projects considering the prolonged and highly complex supply processes of the materials that involves many uncertainties with many stakeholders requiring high level of coordination and collaboration in addition to the coordination of the multiple construction materials from different resources. With the impact of the increased unethical and unreliable practices in the construction industry and thus the raised awareness about the construction material quality in the recent years, the efficient tracing and the transparent monitoring of the construction materials with their supply chains in terms of the material quality achieved under solid material tracing systems have become essential for construction and building safety, in addition to the operational efficiency of the construction projects and their exponentially increasing demand for the previously determined high quality standards. So, tracing the construction materials' quality during the different stages of the material supply chains is crucial for actually achieving these goals of the safe and high quality construction practices with overall success in the construction projects; on the other hand, most of the existing material tracing systems are centralized systems with limitations depending on responsible parties and thus creating possible threats of trust, security, serviceability, traceability, transparency, and integrity. The advancement of technologies in recent years including blockchain and smart contract technologies enable new tools to create innovative and effective solutions to the current difficulties in managing materials' origins, movements, visibilities, logistics, inventories, and compliances. With a blockchain based construction material tracing system which is designed to provide a secure, transparent, and trustworthy platform for tracing and monitoring the information for production, design, transportation, construction, testing, and operation stages of all the construction materials, new ways to overcome these possible problems of the centralized material tracing systems can be obtained. Therefore, the main objective of this study is to present a smart contract powered blockchain based construction material tracing framework that ensures the transparent monitoring of all the suppliers and the quality, safety, and reliability of the construction material supply chains during the entire processes.

The proposed framework is designed to work as an alternative that improves construction quality management demands with increased efficiency and credibility in the monitoring and traceability of material supply chains. The material tracing system eliminates or reduces the limitations of traditional centralized models with the help of blockchain technologies by improving the materials' accessible information and secured data flow among various stakeholders of the chains, and thus minimizing the possible problems and uncertainties that affect the quality of the materials, in addition providing convenient management and coordination of the multiple construction materials from different resources. This study is organized as follows: With the literature review section, the existing researches and works in addition to the possible contributions of the proposed framework to the existing systems are discussed, while the details of the proposed framework and the used tools for its application are given in the procedure section. And finally in the discussions and conclusion section, the advantages with possible variations of the proposed framework are discussed in addition to the concluding remarks made for a more efficient and transparent construction material tracing system in the construction industry with smart contracts together with recommendations for the future research directions.

Literature Review

With the help of the new advancements in the technologies, the blockchain and smart contract based systems have been started to be used as an efficient solution for the ongoing problems and limitations of the supply chain processes in many sectors including the construction industry projects. As Flanagan et al. (2023) mentioned supply chain management is one of the industries that benefit from the advancements in the blockchain technologies, so there are several blockchain and smart contract frameworks that have been proposed especially for supply chain management. Also considering the limitations of the traditional systems such as the fragmentation, lack of trust among the stakeholders of the processes and the restricted information sharing about the materials as stated in Basheer et al. (2024), the blockchain and smart contract based systems can be a solution since they improve the traceability and transparency for the supply chain material information and create an environment with high level of accountability and trustworthiness among the stakeholders in the different stages of the processes. Moreover, Kulkarni et al. (2023) and Turjo et al. (2021) stated that the existing supply chain processes, which may include untrustworthy organizations during the entire process from raw material extraction to the ultimate consumption of a finished product and thus are ineffective and untrustworthy for consumers, can be replaced with the utilization of the smart contracts with trackable, irreversible, and credible performances and blockchain technologies that protect data from unauthorized access without the involvement of third parties. Similarly, Singh et al. (2023) mentioned that the construction industry is also one of the main industries that faces the significant challenges regarding supply chain transparency including the lack of visibility, and the difficulties in tracing material origins, tracking movement, and ensuring compliance in the current practices, while the blockchain technology has emerged as a promising solution to enhance supply chain transparency and sustainability in the construction industry. Furthermore, Xu et al. (2023) stated that there are some persistent issues related to material fraudulence in the construction industry, that have high level of complexity with prolonged supply chains and numerous stakeholders, considering that the current strategies of managing construction logistics and supply chain confuse provenance tracing and tracking by adding too many intermediaries and using low technologies, yet with the help of the blockchain based frameworks the management of quality, safety, payment, logistic and supply chain, and sustainability can be improved significantly. Udokwu et al. (2021) presented an example Construction Project Management platform that is based on blockchain and smart contract technologies for enabling peer-to-peer collaboration between construction parties that enhances the flow of information for reducing cost and time expenditures while improving the quality of services.

The abovementioned advantages of the blockchain and smart contract applications can be utilized also in the material quality control processes where the production must meet certain standards that range from Quality Control (QC) to the quality of the used materials (Gaiardelli et al., 2022). While Tian and Zhong (2020) proposed a comprehensive quality management system that includes everyone from raw material suppliers to consumers base on the advantages and characteristics of blockchain technology in view of the difficult problems in quality management, Gayialis et al. (2022) mentioned that there is an increasing need and demand in recent years for effective traceability due to the growing consumer awareness of the quality of products in the wine industry considering the impact of visibility loss of the product origins to the production and distribution processes and the serious fraud risks. A similar perspective can be achieved in the tracing of construction materials during the different stages of the supply chain processes, which requires complex material tracing systems with high level of coordination and collaboration among the stakeholders; however, there is still limited research of blockchain and smart contract frameworks that have focused specifically on tracing of the construction materials quality. In the construction industry, the project owner, the supervisor, the construction unit, the testing enterprise, and the material supplier are closely combined as the quality and safety stakeholders and by the blockchain technologies, they are all linked to the quality problems caused from raw material quality to non-standard operations; moreover, through the application of advanced technologies such as blockchain, the scientific and technological level of construction quality management, including the intelligent control, quality traceability and trusted quality inspection evidence chain management methods for the whole process, has been improved significantly (Wang et al., 2023). Panda et al. (2022) provided an example study by mentioning that in comparison to many other industries, the construction industry can be termed as one of the world’s most fragmented sectors due to the scattered and complex supply chains considering the various factors involved like the clients, architects, contractors, material suppliers, and the globally manufactured construction products that have to be managed for the sake of meeting the quality requirements and customer satisfaction, and presenting blockchain inspired technologies to maintain the transparency among the actors involved in construction industry and prevent any form of miscommunication.

So, this study aims to contribute to the existing literature by proposing a blockchain based construction material tracing framework for specifically tracing the construction materials during the supply chain processes in terms of the material quality to improve the materials' accessible information and secured data flow in addition to the coordination and collaboration among various stakeholders of different stages, together with minimizing the uncertainties related to the materials and possible unethical practices.

Procedure for the Proposed Blockchain Based Tracing Framework

In this study, a novel smart contract powered blockchain framework for construction material tracing, that ensures the transparent monitoring of all the suppliers, stakeholders and the quality, safety, and reliability of the construction material supply chains during the entire supply chain processes of the construction projects, is designed and proposed for secure, transparent, and trustworthy tracing and monitoring of the information from the raw material extinction and the transportation to the quality testing stages of all the required construction materials. The proposed quality tracing framework consists of a blockchain integrated decentralized smart contract to execute the works of accessing, storing, and validating the material information throughout the supply chain processes, which are used for the quality testing and assurance, and the coordination between the stakeholders of the different stages as the owner/employer, contractor, and suppliers. The tracing framework starts with the owner's adaptation and implementation of the smart contract module, which is monitored by the MetaMask system that controls the user access to the module for the integration of the Ethereum blockchain system with the usage of the various stakeholders including the suppliers and the contractors to upload the related documents of the used construction materials' information required for the quality assurance in addition to reviewing, confirming and validating these materials' information in a secure, transparent, and trustworthy platform.

The owner determines the required documentation and controlling criteria including the certificates, reports, analysis results, procurement documents, and transportation history of all the supply chain processes of the construction materials decided to be used in the related construction projects to prove that these selected materials are actually meet the desired quality standards of the project. Then all the suppliers and the contractors who can access the smart contract module with their assigned MetaMask profiles upload the related requested documents to the owners' computer and the contractors' computers and trace, review, confirm and validate these information in addition to updating them throughout all the supply chain processes with the help of the system to prove that the required level of quality and level of standards for construction materials used to perform the project are achieved. The framework completes with the smart contract identification of the qualified materials when all the stakeholders confirm the accuracy of the provided information in the documents needed for the approval of the required quality standards of the materials used in the projects while the information of the regarding stakeholders that provide the qualifications of the approved materials used in the project kept disclosed through the system to the other users, which makes the whole process highly transparent (Ahmadisheykhsarmast et al., 2023).

For the decentralized smart contract module of the proposed framework, the usage of the Ethereum blockchain is considered due to its qualifications as scalability, security, privacy, maturity, throughput, cost, efficiency and data storage, based on the blockchain decision framework for project management applications presented by Sonmez et al. (2023). The smart contract module of the proposed blockchain based smart contract framework system is required for the execution of all the stages of information uploading, generating and recording of the CID hashes, information validation, information tracking, interactions among the stakeholders, validation and status tracking of the used construction materials' qualifications, managing the complex material tracing without the involvement of a trusted or third party with the authorized account management and access to the Ethereum blockchain. Moreover, Ahmadisheykhsarmast et al. (2023) presents a well-established, transparent, and traceable platform for securely storing and distributing the data with blockchain technology to produce unique irreversible cryptographic identifiers called content identifier (CID) for each and every data that contain requested material quality qualifications uploaded by the stakeholders of the supply chain processes, and since these generated CID's change whenever the content of a document is altered, the transparent tracking and monitoring of all the construction materials used in the related projects can be achieved during the entire processes. Furthermore, due to the relatively small digital sizes of these generated CID's, they provide convenient and cost efficient storage and distribution on the blockchain Ethereum.

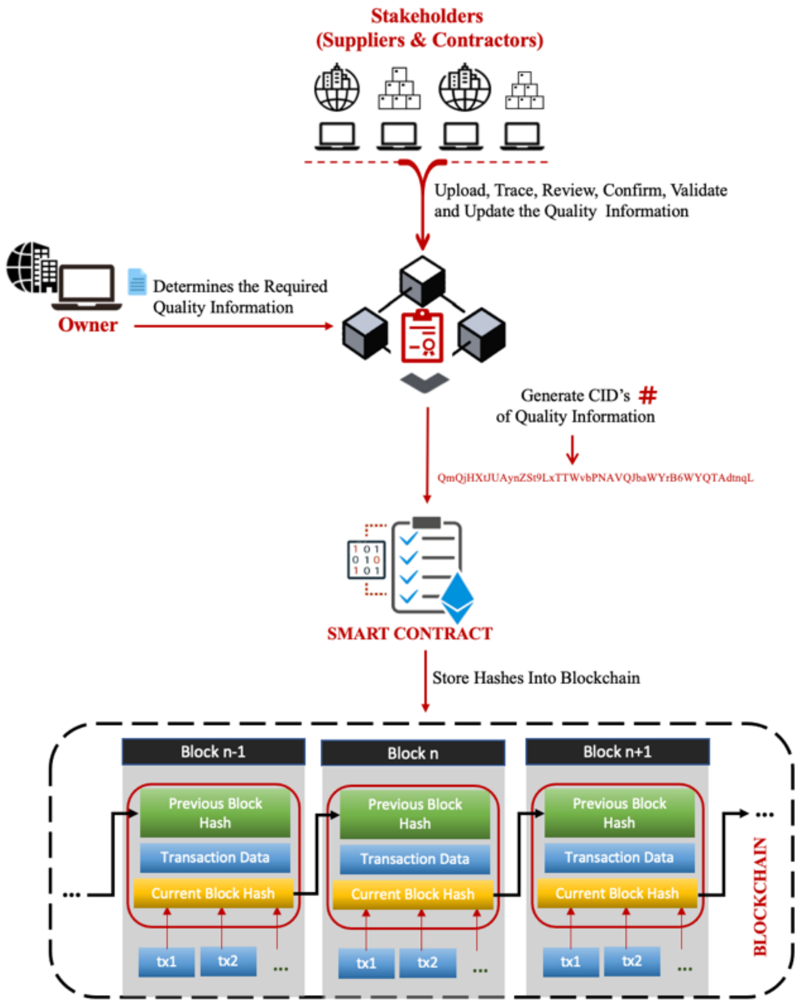

Figure 1: The proposed smart contract powered blockchain framework for construction material tracing (Ahmadisheykhsarmast et al., 2023).

So, the proposed framework for the construction material tracing can improve the construction quality management demands as the quality, safety, and reliability of the construction material supply chains with increased efficiency and credibility in the monitoring and traceability considering that specific hashes/hyperlinks representing unique content proof CID's are created for every information of the used construction materials during the each step of the processes used by all the stakeholders to access the required information, increase the transparency of the material tracking processes. In case of a dispute between the owner and the contractor about the supply chain documents CID's will serve as a proof. Additionally, the proposed framework provides significant improvement by using multiple nodes to avoid single point of failure and working properly even if one or a few nodes fail, and improved data integrity and security of the materials' information by tracking the malicious attempts and possible unethical practices.

Discussions and Conclusion

The presented smart contract powered blockchain framework for the construction material tracing system of the supply chains in terms of the material quality assurance proposed as an effective solution for the existing problems and limitations in the construction industry like the difficulties in managing materials' origins, movements, visibilities, logistics, inventories, and compliances by providing a secure, transparent, and trustworthy platform for tracing and monitoring of all the quality, safety, and reliability of the construction material supply chains during the entire processes, which possess significant importance for the construction and building safety and quality, in addition to the operational efficiency of the projects considering the prolonged and complex supply processes of the construction projects.

The proposed framework is intended to improve construction quality management demands with increased efficiency and credibility in the monitoring and traceability of material supply chains by eliminating the limitations of traditional centralized models with the help of blockchain technologies, minimizing the possible problems and uncertainties that affect the quality of the materials, and providing convenient management with coordination and collaboration of the multiple construction materials from different resources, in addition to improving the materials' accessible information and secured data flow among various stakeholders of the chains. The proposed framework also provides various benefits in a broad range considering the possible improvements in the cost and security analysis, data security and integrity, anonymity and privacy with the authentication and access control, and resilience to the cyber-attacks. The benefits regarding the cost analyses can be obtained considering the decrease in the administrative costs with the elimination of the trusted third parties who perform all the required processes for the quality tracing of the construction materials by the decentralized nature of the blockchain framework, although the integration of the Ethereum blockchain requires a transaction fee paid to the network. Moreover, a secure, transparent, and trustworthy platform with data integrity throughout the tracing and monitoring processes creates advantages in terms of the data security and integrity with the secured and protected material information, which cannot be distorted, altered, or removed without the authorized digital signatures, throughout the different stages of the supply chain by the implementation of the public key cryptography mechanism. Additionally, various benefits are obtained with the improved transparency of the processes and the traceability of the construction materials achieved with the proposed framework by the creation of unique CID's stored in the Ethereum blockchain, that are sensitive to any modification in the information they represent and thus traceable in the network, and thus reducing the possibility of unethical practices and data leakage in addition to the data manipulation issue that often arises from centralized cloud service providers. Finally, by offering convenient management of coordination and collaboration among stakeholders, the presented framework increases the workability and trustworthiness of the system, while the anonymity, privacy and resiliency to malicious cyberattacks advantages are achieved by the authentication and access control gained with the MetaMask system and public keys provided to the various types of stakeholders depending on their usage of the modules considering the removal of the trusted third parties in the construction material information validation, material tracing, and monitoring processes, and the help of the decentralized and distributed nature of the blockchain technologies that can function normally even in the event that one or more nodes are unavailable.

To conclude, in this study, a smart contract powered blockchain framework for the tracing system of the construction materials is presented considering the raised awareness about the construction material quality in the recent years with exponentially increasing demand for the high quality standards due to the impact of the increased unethical and unreliable practices in the construction industry, and the crucial necessity of the efficient and transparent tracing of the construction materials with their supply chains in terms of the material quality for construction and building safety, in addition to the operational efficiency of the construction projects. The blockchain and smart contract technologies are used for the design of the proposed framework to offer a safe, transparent, and reliable platform for tracking and ensuring the required quality information for the approval of the construction materials' compliance with the specified quality standards. With the help of the created advantages of blockchain and smart contracts, that covered in detail in this study, the proposed system offers an effective alternative to the traditional centralized material tracing systems, which have limitations regarding to trust, security, serviceability, traceability, transparency, and integrity, and improves security, privacy, transparency, and fairness while lowering the need for a trusted third party and mitigating unethical practices and fraud. Finally, some future research directions can be recommended as the fully autonomation of the proposed tracing system by eliminating the involvement of the stakeholders during the validation processes of the required quality information of the construction materials by the integration of artificial intelligence for achieving an improved decentralized construction material tracing system in the construction industry.

References

Ahmadisheykhsarmast, S., Senji, S. G., & Sonmez, R. (2023). Decentralized tendering of construction projects using blockchain-based smart contracts and storage systems. *Automation in Construction*, *151*, 104900. https://doi.org/10.1016/J.AUTCON.2023.104900

Basheer, M., Elghaish, F., Brooks, T., Pour Rahimian, F., & Park, C. (2024). Blockchain-based decentralised material management system for construction projects. *Journal of Building Engineering*, *82*. https://doi.org/10.1016/j.jobe.2023.108263

Flanagan, E. W., Shukla, V. K., Suresh, D., & Preetha, V. K. (2023). Enhancing traceability within supply chains through smart contracts. In *Emerging Applications of Blockchain Technology*.

Gaiardelli, S., Spellini, S., Pasqua, M., Ceccato, M., & Fummi, F. (2022). Integrating smart contracts in manufacturing for automated assessment of production quality. *IECON Proceedings (Industrial Electronics Conference)*, 2022-Octob. https://doi.org/10.1109/IECON49645.2022.9968887

Gayialis, S. P., Kechagias, E. P., Papadopoulos, G. A., & Kanakis, E. (2022). A smart-contract enabled blockchain traceability system against wine supply chain counterfeiting. In *IFIP Advances in Information and Communication Technology, 663 IFIP*. https://doi.org/10.1007/978-3-031-16407-1_56

Kulkarni, S., Wireman, J., & Tabrizi, N. (2023). Framework for design and development of blockchain applications using smart contracts. In *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 14206 LNCS*. https://doi.org/10.1007/978-3-031-44920-8_8

Panda, S. K., Daliyet, S. P., Lokre, S. S., & Naman, V. (2022). Distributed ledger technology in the construction industry using Corda. In *The New Advanced Society: Artificial Intelligence and Industrial Internet of Things Paradigm*. https://doi.org/10.1002/9781119884392.ch2

Singh, A. K., Kumar, V. R. P., Irfan, M., Mohandes, S. R., & Awan, U. (2023). Revealing the barriers of blockchain technology for supply chain transparency and sustainability in the construction industry: An application of Pythagorean FAHP methods. *Sustainability (Switzerland)*, *15*(13). https://doi.org/10.3390/su151310681

Sonmez, R., Sönmez, F. Ö., & Ahmadisheykhsarmast, S. (2023). Blockchain in project management: A systematic review of use cases and a design decision framework. *Journal of Ambient Intelligence and Humanized Computing*, *14*(7), 8433–8447. https://doi.org/10.1007/s12652-021-03610-1

Tian, L., & Zhong, X. (2020). Construction of quality management system based on blockchain and its evaluation system based on AHP-BP. *Proceedings - 2020 Management Science Informatization and Economic Innovation Development Conference, MSIEID 2020*, 402–407. https://doi.org/10.1109/MSIEID52046.2020.00086

Turjo, M. D., Khan, M. M., Kaur, M., & Zaguia, A. (2021). Smart supply chain management using the blockchain and smart contract. *Scientific Programming*, *2021*. https://doi.org/10.1155/2021/6092792

Udokwu, C., Norta, A., & Wenna, C. (2021). Designing a collaborative construction-project platform on blockchain technology for transparency, traceability, and information symmetry. *ACM International Conference Proceeding Series*, 1–9. https://doi.org/10.1145/3456126.3456134

Wang, H., Xu, X., Xie, W., Zheng, H., Liu, J., & Li, J. (2023). Research on traceable quality control method for cast-in-situ concrete of transmission line. *Proceedings - 2023 Panda Forum on Power and Energy, PandaFPE 2023*, 510–515. https://doi.org/10.1109/PandaFPE57779.2023.10140972

Xu, J., Lou, J., Lu, W., Wu, L., & Chen, C. (2023). Ensuring construction material provenance using Internet of Things and blockchain: Learning from the food industry. *Journal of Industrial Information Integration*, *33*. https://doi.org/10.1016/j.jii.2023.100455

Targets in Augmented and Virtual Reality Technology Applications in The Construction Industry

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Abstract

Technology is one of the areas where change and development are most intense in our world. Technology is used extensively in almost all sectors and has significant contributions to industries. While the application areas of technology in the construction industry are also large, these changes, conversions and applications are slower than other industries. In the developed countries of the world, technology adaptation for the construction industry is seen to be faster and more widespread than our country. In this study, articles, theses and researches on virtual reality and augmented reality in the construction sector were examined and the research results and the goals of digitalization in the sector were listed. In determining the targets, the criteria were determined in the interviews with the sector employees and the order of the criteria was determined with the Best-Worst Method. According to the weightings determined, increasing the profit rate, which is the most significant benefit offered by virtual and augmented reality for construction projects, stands out as one of the primary objectives of technology adoption in the construction industry, mirroring findings from other studies.

Keywords: *augmented reality, digitalization, mixed reality, technology, virtual reality.*

Introduction

Progress is a fundamental trait of human beings. The essence of this inherent trait is the cornerstone of the engineering profession, driving forward the wheels of technological progress. The 21st century stands as a beacon of unparalleled technological progress. Significant fields including science, commerce, medicine, communication, and myriad others have reaped immense benefits from the progress in technology.

This interaction, destined to endure throughout human existence, serves as a profound catalyst for the dissemination of knowledge and the pursuit of new inventions. In fact, humankind's prowess in making discoveries has expanded to such an extent that we now witness the occurrence of multiple innovations within the same field simultaneously. Hence, the relentless surge of technological progress, continually stretching the boundaries of human understanding, propels humanity toward entirely novel horizons with each passing moment, ushering in transformative shifts in human existence.

Technological progress makes substantial contributions to a multitude of disciplines, both theoretical and practical. The success of developed nations is underpinned by their utilization of technological progress, effectively integrating it into practical applications. The adept handling, assessment, and transmission of information represent one of the paramount domains in which these nations have achieved remarkable success. The effectiveness of these initiatives has steered countries aspiring to robust future planning towards closely monitoring technological advancements in delivering information, audio, and visual content. The societies of the future are constructing their foundations on what we presently call information technologies. Hence, it is imperative to ensure that the current technological infrastructure is positioned to its fullest potential. Failing to do so may lead societies to grapple with increasingly intricate and challenging issues in the years ahead. Given the advantages they offer, virtual reality (VR), augmented reality (AR), mixed reality (MR), and extended reality (XR) applications rightfully claim significant and indispensable roles across numerous sectors.

While the construction industry certainly leverages technology, other industries often enjoy more extensive benefits from technological advancements. Specifically, the automotive, furniture, and health industries are swiftly embracing technology, effectively addressing shortcomings and closely tracking technological advancements.

Technological application areas in the construction industry are quite wide. Starting from the planning stage, technology applications can be used at all stages such as construction, control, delivery, maintenance and renovation. These applications include applications and devices such as VR, AR, drones.

Virtual Reality

VR represents one of the environments crafted within the virtual realm, offering avenues for exploration. It has spurred the development of a wide array of other applications. VR can be described as a human-computer interface enabling users to interact and immerse themselves within computer-generated environments. VR, often categorized as an interaction modality, is a specialized environment that harnesses various effects to augment the user's real-world experience through computer-generated visuals, audio, and textual content.

VR is a computer simulation employing a specialized digital system integrated with sensors, enabling lifelike interaction within a three-dimensional image or environment (Whyte et al., 2003). Pivotal researcher in the historical progression of virtual reality is Ivan Sutherland, whose creation of Sketchpad in 1963 marked the inception of the world's first interactive computer graphics application. Sutherland, alongside his students Bob Sproull, Quintin Foster, and Danny Cohen, is also credited with developing The Sword of Damocles, recognized as the world's first head-mounted virtual reality device (Sherman & Craig, 2019).

An examination of virtual reality applications within the construction industry unveils the following insights:

The construction industry and its management have emerged as ambitious frontiers for the implementation of VR. The abundance of opportunities for application in the construction industry has spurred experts to delve into researching the optimal utilization of VR technology. VR holds significant promise for successful applications across various facets of the construction industry, including project planning, progress monitoring, work management, worker training, time and cost analysis, quality management, and sales processes (Ahmed, 2018).

The construction industry, leveraging technological advancements to their fullest extent, has forged significant pathways for utilization within the realm of VR. The construction industry has acknowledged the invaluable advantage of VR's immersive, three-dimensional experience as a pivotal tool for human interaction. Furthermore, VR introduces a modern and highly effective facility management system, elevating the capabilities of project authorities to a level of satisfaction previously unparalleled (Koch et al., 2014).

Dedicated efforts on this topic in recent years have yielded fruitful outcomes. VR holds immense promise for the future, offering solutions that cater to the desired expectations of project owners, managers, and workers alike, thereby promising significant contributions across the construction industry (Behzadi, 2016). Before the integration of VR technology into the construction realm, error management was both costly and time-intensive. However, thanks to VR technologies, error management has become remarkably straightforward and efficient, eliminating the need for physical labor. Consequently, resource savings are achieved through more efficient management of labor, costs, and time (Yenigün et al., 2020).

Deaths and injuries resulting from construction accidents, which escalate annually, represent a significant challenge that the construction industry must actively strive to prevent. Hence, one of the paramount concerns in construction projects revolves around the training of employees. This is because construction quality and worker safety often hinge on the thorough, ongoing, and effective training of workers (Demirkesen & Arditi, 2015). Through the integration of simulation into Building Information Modeling studies, VR glasses were employed, culminating in a thesis study demonstrating the potential for a heightened and more realistic perception of images. The VR image is presented in Figure 1 (Koyun, 2017).

Figure 1: VR sample image.

Augmented Reality

AR can be defined as an enhanced view of the real-world environment and its contents, overlaid with computer-generated audio, video, graphics, and GPS data, either in real-time or indirectly. This technology, which initially found application in fighter pilots, has since expanded its presence across numerous fields today. These fields include:·education and humanities, ·protection from natural disasters and nuclear accidents, ·art, advertising, and marketing, ·entertainment, health, and museology, ·GPS and geotagging, ·engineering, military, and security (İçten & Bal, 2017).

The concept of AR was introduced in 1992 by Thomas Preston Caudell, a researcher at Boeing, who developed an AR application for industrial use to display assembly designs. AR is defined as a technology that seamlessly integrates virtual objects into real environments, enabling real-time interaction (Azuma, 1997). Another domain where AR is effectively utilized is the architecture and construction industry. AR applications enable the visualization of 3D models overlaid on a 2D architectural plan, allowing for a comprehensive view of both the exterior and interior of the planned building (Gökçearslan, 2016).

Research on the application of AR in the construction industry has been on the rise in recent years. The growing adoption of this technology in construction industry applications offers substantial advantages to the sector. For instance, AR provides the opportunity to visualize a structure before it is built, allowing for the preemptive implementation of precautionary measures.

A study on occupational safety underscores the impracticality of training new heavy construction equipment operators on-site under real conditions due to the significant expense, logistical challenges, safety risks, and difficulty of control. With the AR model ARTS, rather than undergoing impractical real field training, operators are trained within a real construction site environment equipped with authentic heavy construction equipment, virtual materials, and virtual targets (Wang & Dunston, 2006).

In one study, AR technology was employed to create a system that provides workers, equipment operators, engineers, and managers involved in construction projects with stage-by-stage information from the initiation to the completion of manufacturing tasks related to construction or control. In the system developed with smart glasses, users can access training and construction methods relevant to their tasks directly on the job site, enabling instant access to necessary information about production while undertaking construction or control tasks (Kıvrak & Arslan, 2018).

In 2015, D. Parmar developed an application aimed at enhancing the graphic technical knowledge of students enrolled in engineering departments. This application is compatible with all Android-based mobile devices as well as desktop computers running on various operating systems (İçten & Bal, 2017).

In another study, a review of numerous articles and theses related to AR led to the conclusion that AR was applied for three primary purposes: reducing project costs through the application of digital technologies, saving time, and enhancing safety and quality for construction works and workers (Hajirasouli et al., 2022).

Best-Worst Method

The Best-Worst Method (BWM) was introduced to the literature of multi-criteria decision-making methods by Rezaei in 2015 (Rezaei, 2015). Compared to other methods, BWM stands out for its ability to facilitate evaluation with a small number of pairwise comparisons and its straightforward calculation process. As a result, it has earned a place in the literature among subjective criteria weighting methods (Aşan & Ayçin, 2020). The BWM is a method that computes evaluations by establishing preferences of the most significant criterion over other criteria, as well as preferences of other criteria over the least important criterion. The implementation process of BWM involves six stages (Rezaei, 2015).

Step 1: Criteria {C1, C2, ..., Cn} appropriate to the decision problem are determined. Step 2: The best (most important) and worst (least important) criteria are identified from among the criteria by taking advantage of expert opinions. Step 3: The preference level of the criterion with the best importance over the other criteria is determined. Saaty's 1-9 scale is used to determine this level. Step 4: Preference levels of all criteria are determined according to the least important criterion. Again Saaty's 1-9 scale is used to determine this level. Step 5: Criteria weights (w1*, w2*,…,wn*) are calculated. WB: Weight of the best criterion, WW: Weight of the worst criterion, ABi: Razei formulated the linear BWM (1) as follows: the importance of the most important criterion relative to criterion i, the importance of criterion AiW: i relative to the least important criterion. The final stage is to test the consistency of the evaluations made. The values in the table of consistency index values are used here. Consistency index values shown in Table 1 are used in the calculation. Taking values between 0 and 1, a consistency ratio close to 0 means that consistency is high and close to 1 means that consistency is low.

Table 1. Consistency index table.

aBW	1	2	3	4	5	6	7	8	9
Consistency Index (max ξ)	0.00	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

Purpose of the Study

The construction industry is evolving into a realm of increasing complexity. Especially the demand for executing specialized and consecutive tasks within tight deadlines elevates project risk and often results in errors in the time, cost, and quality triangle. Technology and digitalization, essential tools in error reduction across all sectors, have become indispensable for the construction industry. In recent years, Building Information Modeling has emerged as a crucial tool, particularly for construction projects facing tight deadlines.

Technological applications encompass a wide array of tools, including computer software, VR, AR, MR, XR, digitalization, digital twin technology, and more. The objective of this study is to analyze articles, theses, and research on VR and AR in the construction sector, with the aim of identifying the areas where maximum benefit can be derived from applications of VR and AR.

Determination of Criteria for BWM

The applications of virtual and augmented reality, crucial components of digitalization, remain relatively limited in Türkiye at present. In order to determine the areas where maximum benefit can be obtained from virtual and augmented reality applications, articles, theses and researches on virtual and augmented reality in the construction sector were analyzed at this stage. As a result of these analyzes, the following criteria were determined. The criteria obtained were then evaluated in interviews with experts; Determining the best and worst criteria and ranking from the best criterion to the others was made. The number of experts interviewed is 15 people. 11 civil engineers and 4 architects were interviewed. Of the experts interviewed, 11 people have 15-20 years of experience and 4 people have less industry experience.

The criteria are determined as follows: Increasing quality (Striving to maximize quality throughout the project phases), Minimizing errors (Detecting errors before they occur during the project phases and intervening promptly if an error arises), Maximizing profit rate (Endeavoring to maintain the profit rate at the highest level through applications), Rapid access to desired information (Seeking to access necessary information as quickly as possible, particularly in complex structures), Expanding market share (Aspiring to reach and influence a wider range of buyers through applications), Occupational health and safety (Aiming to minimize or eliminate occupational accidents), Streamlining documentation (Working to minimize the significant time and cost associated with procedures and archiving due to the need to maintain every document).

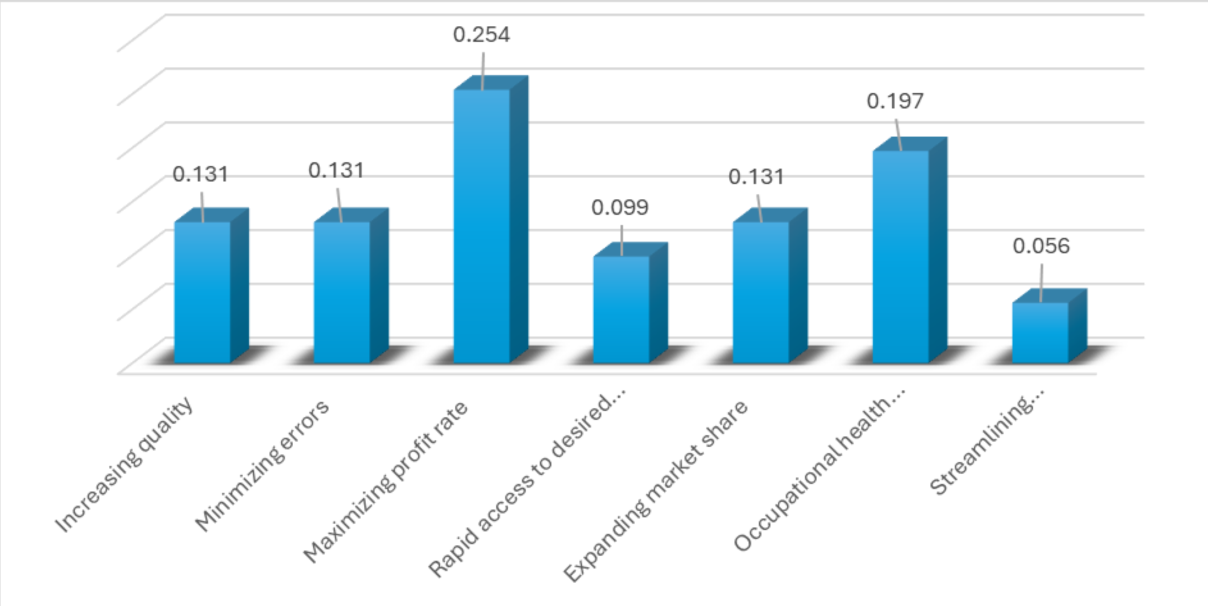

Figure 2: Best-worst method / determined weightings.

In the interviews with experts, the criterion deemed the most favorable was increasing the profit rate, while the criterion considered the least favorable was minimizing documentation. Using the Best-Worst Method, weightings were determined based on the outcomes derived from selecting the best choice and the worst choice. According to the results obtained from the application, the ranking of goals with virtual and augmented reality determined that increasing the profit rate held the first place, while minimizing documentation ranked last. Figure 2 shows the weightings determined.

According to the weightings determined, increasing the profit rate, which is the most significant benefit offered by virtual and augmented reality for construction projects, stands out as one of the primary objectives of technology adoption in the construction industry, mirroring findings from other studies. This observation underscores that the primary goal in digitalization is the profitability derived from the investment Examining the ranking, occupational safety emerges as the second most important criterion. The least significant criterion among the targeted objectives is documentation, despite its importance for sustainability and environmental conservation, as it often leads to archiving issues. Minimizing documentation appears to be of least importance among the criteria.

Results

Our world, continually shaped by technological innovations, is transitioning into a more computer-centric existence with each passing day. This rapid transformation precludes the possibility of returning to our lives as they were before. Today's humans, transitioning from a mobile lifestyle to a mobilized existence, are evolving towards a living model that craves communication in a borderless universe, driven by the necessity for rapid access. The needs arising from this change and development spur numerous innovations in human usage.

Among the promising innovations are VR and AR. These two applications maximize the utilization of technology across every sector. Compared to other sectors globally, the construction industry lags behind in terms of digitalization and technology adoption. Especially in Türkiye, the construction industry is not at the desired level in terms of digitalization and technology adoption. There are likely several reasons why the construction industry in Türkiye has not reached the desired level of digitalization and technology adoption. Some factors contributing to this situation include the high initial investment and maintenance costs associated with digitization, lower levels of education among workers, insufficient training on VR-AR products in our country, challenges in adapting to innovation, and even resistance from employees. Furthermore, the presence of numerous subcontracting firms may hinder full integration.

To list the passive benefits of these applications step by step:

Taking into account the inception, completion, and ongoing management of a project, VR and AR applications can be leveraged to their fullest extent at each stage.

During the planning phase, transferring projects to a virtual environment enables various decisions to be made, such as assessing the sustainability of the building to be constructed on the site and optimizing energy-saving measures.

It aids in critical decisions such as material selection during the implementation phase and facilitates the detection or intervention of errors overlooked during the project phase. It can also provide maximum benefit in safeguarding worker health. Moreover, it will assist in reducing time and waste associated with paperwork and administrative procedures.

Following project completion, in scenarios such as maintenance and repair, it facilitates prompt intervention before damages escalate.

Given that one of the primary objectives of any business is profitability, marketing becomes more streamlined with VR and AR. Customers can be reached swiftly, regardless of their location worldwide, at minimal cost, thereby maximizing market share.

In this study, while increasing the profit rate ranked as the primary objective, occupational health and safety emerged as the second priority. Thirdly, the objectives include increasing quality, minimizing errors, and expanding market share. In fourth place is rapid access to requested documents and information, with minimizing documentation ranking last.

In summary, recent research indicates that VR and AR technology will play a significant role in the future of construction management. It will deliver cost, time, and energy savings through its integration into various facets of the construction industry, while also enhancing productivity by positively impacting occupational and worker health. Moreover, it will serve as an effective communication tool during the sales phase, which is pivotal in the construction industry, streamlining the use of time by obviating the need to visit physical locations. In the coming years, mixed reality (MR) and extended reality (XR) applications are anticipated to propel the sector even further.

All of this research underscores the essential role of technology in the construction industry. Despite lagging behind other sectors for various reasons, it is believed that the construction sector will undoubtedly become more receptive to concepts such as technology and digitalization in the coming period.

References

Ahmed, S. (2018). A review on using opportunities of augmented reality and virtual reality in construction project management. *Organization, Technology and Management in Construction*, *11*(1), 1839–1852. https://doi.org/10.2478/otmcj-2018-0012

Azuma, R. (1997). A survey of augmented reality. *Chaos, Solitons and Fractals*, *42*(3), 1451–1462. https://doi.org/10.1016/j.chaos.2009.03.056

Behzadi, A. (2016). Using augmented and virtual reality technology in the construction industry. *American Journal of Engineering Research*, *512*, 2320–2847. www.ajer.org

Demirkesen, S., & Arditi, D. (2015). Construction safety personnel's perceptions of safety training practices. *International Journal of Project Management*, *33*(5), 1160–1169. https://doi.org/10.1016/j.ijproman.2015.01.007

Gökçearslan, A. (2016). Artırılmış gerçeklik uygulamaları ve grafik tasarım alanına yansımaları. *Turkish Studies*, *11*(19), 267–282.

Hajirasouli, A., Banihashemi, S., Drogemuller, R., Fazeli, A., & Mohandes, S. R. (2022). Augmented reality in design and construction: Thematic analysis and conceptual frameworks. *Construction Innovation*, *22*(3), 412–443. https://doi.org/10.1108/CI-01-2022-0007

İçten, T., & Bal, G. (2017). Artırılmış gerçeklik üzerine son gelişmelerin ve uygulamaların incelenmesi. *Gazi Üniversitesi Fen Bilimleri Dergisi Part C*, *5*(2), 111–136.

Kıvrak, S., & Arslan, G. (2018). İnşaat proje imalatlarında artırılmış gerçeklik teknolojisi uygulamaları. *Journal of Polytechnic*, *21*(2), 379-385. https://doi.org/10.2339/politeknik.385916

Koch, C., Neges, M., König, M., & Abramovici, M. (2014). Natural markers for augmented reality-based indoor navigation and facility maintenance. *Automation in Construction*, *48*, 18–30. https://doi.org/10.1016/j.autcon.2014.08.009

Koyun, H. (2017). Yapı bilgi sisteminin (ybs) Türk inşaat sektöründe verimliliğe etkisi: Simülasyon çözümleri. 1–14.

Rezaei, J. (2015). Best-worst multi-criteria decision-making method. *Omega (United Kingdom)*, *53*, 49–57. https://doi.org/10.1016/j.omega.2014.11.009

Sherman, W. R., & Craig, A. B. (2019). Introduction to virtual reality. In *Understanding Virtual Reality*. https://doi.org/10.1016/b978-0-12-800965-9.00001-5

Wang, X., & Dunston, P. S. (2006). Compatibility issues in augmented reality systems for AEC: An experimental prototype study. *Automation in Construction*, *15*(3), 314–326. https://doi.org/10.1016/j.autcon.2005.06.002

Whyte, J., Centre, I. S., & Campus, S. K. (2003). Industrial applications of virtual reality in architecture and construction. *8(May)*, 43–50.

Yenigün, İ., Yenigün, K., & Erdoğan, S. (2020). Sanal gerçekliğe ticari uygulama yaklaşımları; İnşaat sektörü örneği. *1*, 1–11.

Exploring Digital Twin Applications in the Construction Industry: Opportunities and Limitations

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Abstract

With the advancement of technology, the concept of digital twin (DT), currently used in sectors such as automotive, healthcare, and aviation, is also gaining prominence in the construction industry. The development of the DT concept is expected to play a transformative role in the construction industry. The aim of this research is to reveal the current capabilities and the areas that need to be developed during the DT applications in the construction industry. In this context, a DT software utilized in the construction industry in Turkey was employed to analyze a selected construction site, and the current contributions and shortcomings of the DT were identified. The findings of this study are expected to contribute to enhance the application and utilization of the DT concept in the construction industry.

Keywords: *construction industry, digital twin, technology.*

Introduction

Digital transformation has come to the forefront in the construction industry, as in many other sectors, especially in recent years. With the development of technologies such as augmented reality, mixed reality, internet of things, unmanned aerial vehicles, artificial intelligence, the opportunities to benefit more effectively from the concept of digital twin (DT) are improving day by day. The concept of (DT), which has been used for a long time in areas such as aviation, space sciences and parts production, is becoming a tool that is supported in the production process in the construction industry every day.

The concept of DT was first defined as "digital equivalent to a physical product" by Michael Grieves at the University of Michigan in 2003. A DT is a virtual representation of an object, its parts, or the system to which the object belongs, which uses real-time data to obtain information and make decisions about the process during its life cycle. DTs, which can work in real time and provide the user with the desired information about the simulated object, object part or system at every stage, are not static, but living dynamic entities (Ceylan, 2019).

According to Ceylan (2019) cited in Grieves (2016), there are three basic requirements for creating a DT: a real object in the real world, a virtual object in the virtual world, and a connection between the real world and the virtual world. The system is maintained as a bidirectional dynamic relationship between the real object and the virtual object.

The purpose of utilizing DTs is to respond to a number of needs such as monitoring a real object throughout its lifetime, tracking and controlling its work, ensuring that it works correctly, and testing the changes to be made in the virtual environment before implementing them in the real object. Thus, time losses can be prevented by establishing a cost-process balance. In addition, productivity can be increased in production by contributing to issues such as efficient use of labor, completing the work to be done in a short time and correctly. The technologies used to create a DT include smartphones, video cameras, laser scanning, VR/AR technologies, unmanned aerial vehicles (UAVs), Internet of Things (IoT), artificial intelligence. By using a combination of several of these technologies according to the need, stages focused on data collection, data analysis, data transformation into information and information delivery are provided. The more data can be captured, transformed into information and utilized on a system basis, the greater the value of the DT (Ceylan, 2019).

The aim of this research is to evaluate the construction phase of the DT concept in the construction industry within the framework of a sample. In the scope of the study, the theoretical framework of the DT concept and its implementation in the construction phase within the construction industry were revealed. For this purpose, interviews were conducted with various companies and the data of the companies that offer and utilize DT services in the construction industry were compared. Afterwards, these data were tested with a sample.

Material and Method

The status of DT concept in the construction phase in the construction industry was analyzed in this research. Firstly, companies that provide and benefit from DT services in the construction industry were interviewed, and then a DT was created during the construction phase of a building in a selected sample area. The data obtained as a result of the company interviews and the data obtained during the sample study were compared and the opportunities and limitations of the construction phase of the DT concept in the construction industry were evaluated.

One DT company called BIMCRONE and serving the construction industry in Turkey was selected. In-depth interviews were conducted with authorized employees from BIMCRONE operating in Ankara. Afterwards, in-depth interviews were conducted with authorized employees from TEKÇE İNŞAAT-Antalya Homes, which receives DT service from BIMCRONE in Antalya. Then, a construction site in Döşemealtı district of Antalya province was selected as a sample and the DT of the project was created with BIMCRONE software.

DT in Construction Industry

Although the research on the DT concept in the construction industry is still in at early stage, it is predicted that the DT concept will become more prevalent in the construction industry in the future and even transform the industry. Many actors such as architects, engineers, users and employers are involved in all processes of a building from design to operation. It is also clear that DT technologies will contribute to multidisciplinary studies in terms of the simultaneous accessibility of information about the building by many actors, control of the processes and the ability to intervene in the processes by different stakeholders in cooperation (Ceylan, 2019; Tao et al., 2019). Designers can utilize DT technology to make efficient decisions about the project and thus have a "digital footprint" of the project (Tao et al., 2019). The data collected using the DT can be saved in a database and used by designers in subsequent projects (Qi & Tao, 2018). The DT is also useful for decision-making on issues such as material selection, energy management, and product procurement. Early design decisions such as sustainability and feasibility studies can also be finalized correctly thanks to DT technologies. Other actors involved in the project processes can also participate effectively in the processes, effective planning can be ensured, project processes can be clearly understood by each participant, and what needs to be done at each stage can be realized. All this ensures effective communication, cooperation and mutual trust among project stakeholders (Ilhan & Yaman, 2016; Dubas & Pasławski, 2017). For these reasons, the contributions of DT technologies to the industry are important, especially in high-cost industries. As Sepasgozar (2021) states in his study, the most pressing need in the construction industry is continuous or near real-time data exchange using a secure and high-speed network.

Results

In-Depth Interviews

According to the information received from the service provider; the current DT software is compatible with Windows operating system but does not work with MacOS operating system. On mobile phones, it works compatible with both the IoS and Android operating systems. The company only serves the construction industry. As of June 2023, they have been serving to five companies in Turkey. There are 15 companies that are in the trial phase and using the demo version of the DT software they developed. All of the companies they serve benefit from the DT software at the construction phase. Data input to the system is done manually. According to the information obtained from the company official, the data collection system with unmanned aerial vehicles is not currently preferred due to its weaknesses in terms of data security. However, they plan to analyze and interpret the data with augmented reality (AR) constructions that they purpose to implement in a few years. In this way, it will be possible to interpret the necessity of this need for revision, and to have information about its cost and process. It’s therefore expected to make a positive contribution especially in the decision-making phase in the need for revision. In addition, since the production and DT model progress in parallel with each other during the construction phase, the production cost is lower and the quality is higher compared to the traditional method. At the very beginning of the process, information about the deficiencies to be completed can be obtained and process management can be carried out much more effectively. The initial investment cost is also very low for the current situation. The model installation is completed by the technical team within 1-2 days and is available to different users. Different accounts can be created for different stakeholders such as architect, construction site supervisor, civil engineer, accounting, etc., and thus the areas that are under the responsibility of everyone are opened to individuals. In this way, data security is quite high compared to current conditions. Users can be customized according to processes (E. Burukoğlu, personal interview, 04.03.2024; E. Burukoğlu, personal interview, 20 May 2023; N. Akın Öztabak, personal interview, 15 May 2023)

According to the information obtained from the service provider, the current DT construction provides more holistic information on quantity and cost. As mentioned in the literature, bidirectional data flow is not yet available. Data input to the system is done manually in parallel with the construction phase. In addition, the locations of the building elements in the system can be displayed together or separately. However, information about the components that make up the building element cannot be accessed (reinforcement location in the column, etc.). In this respect, it is not possible to benefit from the DT when there is a need for modification during the usage phase. Access and approval of different people can be provided at different stages. While creating the DT model, models made in Revit software are used. When the project models taken from Revit, which is an object-based software, are transferred into BIMCRONE, the components of the building elements appear piece by piece. For this reason, before starting to create the DT, these elements should be combined and turned into objects (K. Tekçe, personal interview, May 25, 2023).

Field Study Results

The BIMCRONE software, which is currently used to create a DT in the construction industry, was compared with the information obtained in the in-depth interview and the construction process at the construction site selected as a sample.

The construction process of Block A in the project named "ANTALLE" located in the Döşemealtı district of Antalya province was selected as a sample. The rough construction phase is still ongoing at the construction site. While the construction process of the selected project continued with the traditional method on site, the REVIT model of the building was simultaneously integrated into the DT software and experienced. Accordingly, it is observed that the DT provides a holistic view of the process and provides effective process management. Currently, only the data input of the architectural project was experienced. In addition to this, it is anticipated that the holistic perspective will improve if data input of other projects can be provided. In this study`s sample, only one user was defined on BIMCRONE, allowing access to the entire system through a single user. By assigning different users, access to different stages is facilitated, ensuring effective stakeholder participation. In case of the need for revision at the construction site; changes are made in the software in which the model is worked (REVIT), and then the changes made are transferred to the BIMCRONE model. On the other hand, since data cannot be transferred from each project to the BIMCRONE system, it can be said that the digital footprint criterion of the building should be improved. Since the traditional construction process continues at the construction site, the DT had no impact on the sample in terms of labor costs and increased quality of production. Energy consumption monitoring-control, ease in operation and maintenance, and feedback elements have not been experienced since they are related to the usage phase. Since the system does not yet include different equipment such as AR/VR devices and UAVs, the investment cost cannot be said to be high. Lack of cooperation is one of the features that need to be improved. As existing users enter data into the system, collaboration between different disciplines will be improved. Since there is traditional production at the construction site, it cannot be said that the DT causes human error at this stage. However, there is a risk of making mistakes during data input to the system. Regarding the need for space on the construction site, a DT can be created with a computer with sufficient hardware. It can be installed on a computer at the construction site that allows taking images for security purposes, and it may be possible for the site supervisor to routinely update the system. Since data input is done by users in the traditional process, there is no reduction in employment.

Unlike the traditional method, in the construction process carried out with the DT; as seen in figure-1; a lot of information can be viewed and controlled through a single system. Information such as the progress of the process, necessary revisions, stages awaiting approval, quantities can be accessed by different users at different stages. It is also possible to control this access. BIMCRONE, the DT software, offers all these possibilities to its users.

Figure 1: Project informations on BIMCRONE.

For example, the system waits for the approval of the building inspection at the stage approved by the site supervisor and forwarded to the building inspection for control. At this stage, the building inspection gives approval through the system after providing the necessary controls in the field. In addition, if only the building inspection user is defined at this stage, other participants can view the system but cannot intervene in the approval section. From this point of view, it can be said that it contributes to quantity and cost. It is also possible to say that it provides data security by differentiating the authorization of users in access and intervention sections.

In addition to all these, bidirectional data flow is not yet possible due to manual data input to the system. On the other hand, the more data input to the system, the more realistic a DT can be obtained. Currently, architectural data input can be made in the BIMCRONE software, which works with REVIT infrastructure. In some cases, static data input can also be provided in a certain amount. Since the reinforcements in the reinforced concrete cannot be entered, the structural elements in the system are displayed only as column-beam-curtain-slab.

In case there is a need for revision during the control stages (on-site solution in the field, etc.), revisions can also be made in BIMCRONE after the revision is made on the software where the model is produced. In this case, a user must be defined and included in the system for the relevant project author and BIMCRONE company official for revision. Revisions that must be completed in construction area are seen in Figure 2 and Figure 3.

Figure 2: Revisions in pool area.

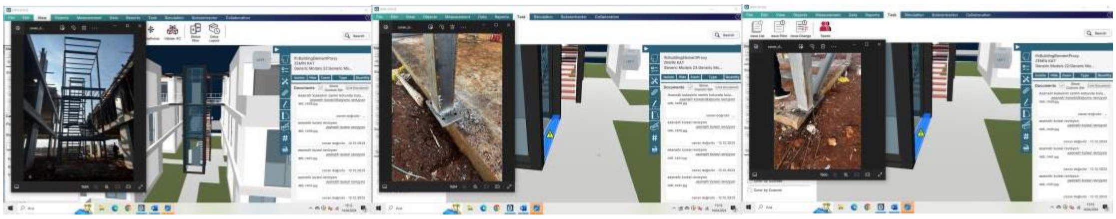

Figure 3: Revisions in elevator area.

Discussion

Utilizing the DT concept at the construction phase in the construction industry offers a holistic perspective on cost and process management under current conditions. It is envisaged that with the transfer of more data to the system in the following processes, the holistic perspective will be integrated more into the process. Additionally, by involving various stakeholders in the system, both the holistic perspective will be improved and the opportunities for cooperation between different stakeholders will increase. Consequently, more effective process management can be carried out compared to the current situation. Broo and Schooling (2021), as a result of their interviews with industry executives in the UK, put forward the idea that DTs will contribute to different stages of the construction industry, and that the products of the construction industry will be built faster, higher quality, lower cost and more sustainably.

It was also observed that the more data can be captured and converted into information on a system basis, the more realistic information the DT provides. In addition, as the possibility of utilizing the information in the DT increases; the value of the DT increases (Ceylan, 2019). This enables the digital footprint of the structure to be obtained. With the digital footprint, potential problems that may be encountered in similar structures to be built in the future can be identified in advance, measures can be taken, and various solutions can be developed in advance.

Currently; stakeholders using the DT can be listed as architects, engineers, construction site managers, building inspection authority. Considering that the DT is currently progressing with a manual data collection system, it is observed that there is no need for extra skilled personnel to benefit from the system. However, in the following processes; it is expected that there may be a need for skilled employees in this regard with the execution of the data collection phase by utilizing systems such as unmanned aerial vehicles and the internet of things. In their study, Broo and Schooling (2021) also addressed the lack of skilled people working in the industry as one of the challenges in the use of DTs in the future. However, according to the information obtained from the BIMCRONE company official; technologies such as unmanned aerial vehicles and internet of things cannot provide sufficient data security at the construction phase in the construction industry (E. Burukoğlu, personal interview, 04.03.2024). For this reason, it is foreseen that these technologies will not be integrated into the system in the near future and that DTs will continue to be created with manual data input. Accordingly, a decrease in employment is not foreseen yet. However, it should be kept in mind that the possibility of human error is high with manual data input.

Alshammari et al. (2021), in their study on the development of the Internet of Things, stated cyber security as one of the biggest obstacles to the development of the DT concept. For this reason, they suggested identifying risks by comparing existing DT constructions, comparing these risks with public policies, and moving forward in cooperation with industries working on cybersecurity. One of the reasons for the current manual data input in the BIMCRONE system is the prediction that the cyber security problem will not be solved in the near future (E. Burukoğlu, personal interview, 04.03.2024).

Peng et al. (2020) stated that DT constructions in the construction industry carry a financial risk due to the investment cost in projects, and even in the absence of careful planning from the design phase; it is almost impossible to add various devices and hardware to the system later. However, in the current situation, only a computer and software are sufficient to create a DT. For this reason, DT constructions are not yet a cost-increasing factor for the construction phase in the construction industry. In the future, as the technologies utilizing the DT become more widespread, it is predicted that the issue of DT initial investment cost will gain importance. In addition, since the hardware required for the DT is a computer and software, there is no need for extra space on the construction site.

Conclusion

In this research, the construction phase of DT in the construction industry was evaluated. The data obtained as a result of in-depth interviews and field study were categorized as the opportunities of the DT in the construction industry and the limitations it currently has.

One of the contributions of the DT concept in the construction industry is, that it provides particularly effective process management and effective stakeholder participation during the construction phase. In this respect, it is obvious that the DT offers a holistic perspective opportunity at the construction phase. Another opportunity is to have a "digital footprint" of the designed building. With the digital footprint, in cases where the building needs to be revised during the usage phase, the information in the invisible parts of the building can be accessed before the revisions (mechanical system, etc.). In the current conditions, a computer and software to create a DT are enough to create a DT of a building. Therefore, the initial investment cost of the DT is low. Since the computer hardware is sufficient to create the DT in the current situation, there is no need for extra space on the construction site. The existing DT software allows different stakeholders to be involved in the system in different processes. Each stakeholder can work on the relevant area, thus data security can be ensured in the system. In summary, DT has the opportunity to be preferred by investors due to its low initial investment cost, no need for extra space on the construction site and data security.

On the other hand, the concept of DT is still developing, especially in the construction industry. For this reason, it has various limitations as well as opportunities. Manual data input to the system still increases the risk of human error. In addition, in case of a different production from the project in the field (on-site solution, etc.), the revision in the field must first be transferred to the model and then to the DT in order for the DT to accurately reflect the building. In case of an on-site solution, the relevant stakeholders in the field should notify this revision to the relevant stakeholders via the DT system and the change in the field should also be revised in the model and DT. Therefore, this step is also a necessary step for the digital footprint. However, there is no regulation in the current system that will make this update compulsory. It is a fact that revisions are left to the initiative of the relevant stakeholders. Leaving it to the initiative of individuals to update the changes made in the DT is another limitation of the DT. In order for the DT to be a dynamic system, bidirectional data flow is required between the building and the twin. In the current system, the fact that data transfer is manual in both directions prevents the process from proceeding simultaneously. The lack of simultaneous progress between the DT and the building can be expressed as a limitation in terms of the need for the DT to be a dynamic system.

The identification of only one company providing DT services in the construction sector in Turkey; the use of the REVIT program to create the DT substrate of the architectural project in the selected sample area; the incompatibility of static, mechanical, and electrical projects with the BIMCRONE system, leading to their inability to be transferred to the DT, and the inability to access cost data for the selected sample structure, constitute the limitations of the study. Despite the defined limitations, it is anticipated that the study will provide practical and theoretical contributions to the literature. The theoretical contribution of the study lies in shedding light on the areas and technologies that need to be developed in the construction phase of the DT concept in the construction industry. The practical contribution of the study can be stated as the realization of the importance of the contributions of the development of DT technologies applied in the construction industry to the construction phase and thus, with the development of these technologies, they can be preferred more by the stakeholders in the industry.

References

Alshammari, K., Beach, T., & Rezgui, Y. (2021). Cybersecurity for digital twins in the built environment: Current research and future directions. *Journal of Information Technology in Construction*, *26*, 159-173.

Broo, D. G., & Schooling, J. (2021). Digital twins in infrastructure: Definitions, current practices, challenges and strategies. *International Journal of Construction Management*, 1-10.

Ceylan, E. Z. (2019). Dijital ikizler ve inşaat sektöründeki yeri. *Yapı Bilgi Modelleme*, *1*(2), 53-61.

Dubas, S., & Pasławski, J. (2017). The concept of improving communication in BIM during transfer to operation phase on The Polish market. *Procedia Engineering, 208*, 14-19.

Ilhan, B., & Yaman, H. (2016). Green building assessment tool (GBAT) for integrated BIM-based design decisions. *Automation in Construction, 70*, 26-37.

Peng, Y., Zhang, M., Yu, F., Xu, J., & Gao, S. (2020). Digital twin hospital buildings: An exemplary case study through continuous lifecycle integration. *Advances in Civil Engineering*, 2020.

Sepasgozar, S. M. (2021). Differentiating digital twin from digital shadow: Elucidating a paradigm shift to expedite a smart, sustainable built environment. *Buildings*, *11*(4), 151.

Tao, F., Sui, F., Liu, A., Qi, Q., Zhang, M., Song, B., Guo, Z., Lu, S. C.-Yu., & Nee, A. Y. (2019). Digital twin-driven product design framework. *International Journal of Production Research*, *57*(12), 3935-3953.

Qi, Q., & Tao, F. (2018). Digital twin and big data towards smart manufacturing and Industry 4.0: 360 degree comparison. *IEEE Access*, *6*, 3585-3593.

Personal Interviews

E. Burukoğlu, personal interview, 04.03.2024

E. Burukoğlu, personal interview, 20 May 2023,

N. Akın Öztabak, personal interview, 15 May 2023

K. Tekçe, personal interview, May 25, 2023

How to Train Your AI for Construction Project Management Research

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Abstract

Advancements in Information and Communication Technology (ICT) are reshaping the Architecture Engineering and Construction (AEC) industry, challenging traditional business practices. Mobile devices and mobile apps, cloud computing, Building Information Modelling (BIM), additive manufacturing are some of the disruptive innovations that are compelling a reevaluation of strategies for enhanced industry efficiency. Among emerging innovations, advances in artificial intelligence (AI) is one of the most debated technological advances of today. Large language models (LLM) have the potential to profoundly impact the AEC industry, akin to other transformative technologies. This paper explores the intersection of AI and AEC research, leveraging a meta-classification framework for literature analysis through an LLM AI tool in an attempt to give an overview to researchers who aim to use these tools for research purposes. The study introduces preparatory steps and compares analysis results with prior research, demonstrating the promising outcomes of AI integration in research processes. Initial findings suggest the potential for faster, more focused, and efficient research outcomes, contingent on effective AI training methodologies. However, there are limitations that researchers should be aware of while using the assessed AI tools for construction management research.

Keywords: *architecture engineering and construction (AEC), artificial intelligence (AI) in research, ChatGPT, construction project management, Gemini.*

Introduction

The recent years have witnessed a surge in technological innovations within the AEC industry, driven by the exponential growth of ICT advancements. The business practices of AEC industry has long been challenged by implementation and adoption of innovative ICT solutions, such as the ones to streamline project delivery processes, enhance collaboration, and improve decision-making. From mobile devices to additive manufacturing, BIM systems to cloud-based project management platforms, the integration of ICT has revolutionized the way projects are planned, designed, and executed (Redwood et al., 2017). In parallel with these ICT advancements, introduction of AI technologies to the wider public have emerged as a game-changer in the AEC industry, offering unprecedented opportunities for automation, optimization, and innovation (Ceylan, 2021). Despite being anticipated as one of the later phases of AI integration, industries reliant on creativity, such as design, found themselves within the core application area of such tools. Within a brief period, there has been a rapid emergence of applications and platforms. They include image generation engines capable of aiding language-based conceptualization, as well as generative space design tools. These tools facilitate the creation of plans and visual representations of optimized space alternatives based on input criteria. However, the field of application is not limited to building designs. Passing through the field of building performance analysis (Pan & Zhang, 2021), construction project management disciple also takes its own share from these variety of tools created by the use of AI technology. Tasks like risk assessment for existing buildings, predictive maintenance, building performance optimization and AI and BIM integration (Pan & Zhang, 2023) are some of the topics of where AI can be used offering opportunities to increase efficiency, precision, and quality.

However, another potential of ICT in AEC is the research capabilities it offers. This potential lies in its ability to facilitate data-driven insights and analytics, paving the way for evidence-based decision-making and knowledge discovery (Davenport & Alavi, 2023). Generative AI, in particular, has garnered significant attention for its ability to mimic human-like text generation, enabling researchers to analyze and interpret textual data on a massive scale. Recent research on Generative AI's problem solving performance show that even the free versions of these tools are capable of solving Project Management Professional exam with remarkable grades (Vakilzadeh et al., 2023). By harnessing the power of large language models (LLMs) and natural language processing (NLP) algorithms, researchers can now unlock valuable insights from vast repositories of textual data, accelerating the pace of research and innovation within the AEC domain.

The integration of AI technologies into AEC research opens up a myriad of possibilities for advancing knowledge and driving industry progress. From predictive analytics and risk assessment (Rokooei et al., 2023) to semantic analysis and sentiment analysis, AI-driven methodologies offer researchers unprecedented capabilities for extracting actionable insights from textual data (Pan & Zhang, 2021). By leveraging AI technologies, researchers can uncover hidden patterns, identify emerging trends, and inform evidence-based decision-making in construction management and related disciplines. This paper represents initial results of a more extensive research on drivers and barriers of innovation in AEC, and it is expected to contribute to the construction project management research agenda.

Literature Analysis Using a Meta-Classification Framework

Literature analysis stands at the forefront of academic research, providing scholars with invaluable insights into existing knowledge landscapes and paving the way for new discoveries (Dickinson et al., 2006). One promising approach to literature analysis lies in the utilization of a Meta-classification framework, which offers a structured and systematic method for categorizing and organizing vast amounts of textual data. By employing such a framework, researchers can effectively navigate through the vast sea of literature, identifying key themes, trends, and gaps in knowledge within their field of study. This meta-classification approach enables researchers to not only comprehend the current state of the field but also to discern underlying patterns and relationships that may not be immediately apparent. Moreover, by synthesizing diverse perspectives and methodologies found within the literature, researchers can gain a comprehensive understanding of complex phenomena and propose innovative solutions to pressing research questions. Ultimately, the adoption of a meta-classification framework empowers researchers to conduct more rigorous and insightful analyses, thereby advancing the frontiers of knowledge and driving meaningful progress in their respective fields.

In recent years, the advent of generative artificial intelligence (AI) has introduced new possibilities for literature analysis within a meta-classification framework. Generative AI models, such as GPT (Generative Pre-trained Transformer), have demonstrated remarkable capabilities in understanding and generating human-like text. Leveraging these advanced AI technologies, researchers can enhance literature analysis by automating certain aspects of the meta-classification process. Generative AI can assist in tasks such as summarizing large bodies of text, extracting key concepts, and identifying relevant categories within the literature. By harnessing the power of generative AI, researchers can expedite the literature review process, uncovering insights more efficiently and effectively than traditional manual methods alone. Furthermore, generative AI can aid in the synthesis of disparate sources, facilitating the identification of interdisciplinary connections, emerging trends across diverse fields of study as well as knowledge gaps (Schryen et al., 2024). However, the lack of research on the opportunities and challenges of the Generative AI for the AEC industry, represents a notable knowledge gap itself (Ghimire et al., 2024). While challenges such as bias and accuracy must be addressed, the integration of generative AI into literature analysis holds immense promise for advancing knowledge discovery and fostering interdisciplinary collaboration in research endeavors. According to the Linkedin Working Report 2024, employees are eager to learn more about how they can use AI in their business tasks with %80, while only %38 of the US executives are currently aiding their employees to become AI-literate (2024 Workplace Learning Report | LinkedIn Learning, 2024).

While the potential of AI technologies in AEC research is vast, several challenges and considerations must be addressed to realize their full benefits. Data privacy, model bias, interpretability, trust (Emaminejad et al., n.d.) and ethical considerations are among the key challenges facing researchers as they navigate the evolving landscape of AI-driven research methodologies. Moreover, the integration of AI technologies into existing research practices requires careful planning, collaboration, and adaptation to ensure seamless integration and optimal outcomes.

Methodology

Data Set Selection

In order to explore the potential of Generative AI on resolving academic texts, a previous research paper by Ilter and Dikbaş (2008) is selected. The mentioned paper analyzes a sample of 63 peer reviewed articles from 5 different international refereed journal publishers' construction management journals published in the last 10 years. The analysis filters the articles using keywords that are searched in title, abstract and keywords sections. The main aim of the paper is to explore the main innovation drivers and barriers using a meta-classification framework. The framework consists of 15 factors under four different categories, namely: Author, Content, Research Style and Identified Drivers and Barriers. After the number of filtered set of articles are finalized by using the publisher's search engines, all the relevant data is collected from the articles using the university library resources personally by the researchers.

Research Structure

Using the same set of factors, this research aims to find out how generative AI can guide researchers to extract data from scholarly articles within the same framework. As the research aims to explore the performance of Generative AI to extract the needed data from articles the previous research by Ilter and Dikbas (2008) is used to validate the results. In order to complete this task the same set of articles used in the research of Ilter and Dikbas (2008) is downloaded as pdf formatted text documents and uploaded to the selected Generative AI interfaces depending on their requirements in pdf or plain text format. Automator 2.10 software is used to convert pdf documents into text where needed. A set of 15 questions that covers the factors of the previous meta-classification framework is developed using the first 10 articles in discussion with the Generative AI interfaces and using the information from web sources like (Kubow, n.d.) and constructive guidance of two academicians working on AI, by separate interviews. Due to their guidance, five key factors that should be considered are identified as follows and the question set is developed accordingly:

- Using clear instructions at every stage of communication,
- Adopting a persona, and setting the stage according to the task needed
- Specifying the format of answers expected before start
- Trying to avoid leading the answer
- Limit the scope

The set of 15 questions that examines the meta-classification framework is used without major changes in the following 10 articles and the initial results are presented in this paper. These questions include a combination of zero-shot and few-shot prompting techniques due to the nature of the queried factors. Further research is planned to complete set of 63 articles of the previous research, and the results are planned to be released in a future research article.

Selecting the Generative AI Tool

As the main aim of this is to understand the performance and capabilities of LLM applications that everyone can reach, in this stage of the research selecting a Generative AI which offers a free plan is considered. Options for the Generative AIs are considered via a quick web search using the "free generative AI for text analysis" query and 5 options are listed in Table-1.

Table 1. Generative AI options considered.

<table>
<tr><th>AI Tool</th><th>LLM base</th><th>Limits of Free Plan</th><th>Data Formats for Interaction</th><th>Limits of Paid Plan</th><th>Cost of Paid Plan</th></tr>
<tr><td>ChatGPT-3.5</td><td>GPT-3.5</td><td>unlimited messages, interactions and history</td><td>Text</td><td rowspan="5">Based on usage tiers</td><td rowspan="5">Variable pricing based on usage</td></tr>
<tr><td>Gemini</td><td>Gemini Pro (Gemini Ultra 1.0 on the paid plan)</td><td>N/A</td><td>Text, Speech</td></tr>
<tr><td>ChatPDF</td><td>GPT-based</td><td>2 files / 120 pages /20 questions</td><td>Text, PDF files</td></tr>
<tr><td>ChatDOC</td><td>GPT-based</td><td>2 files / 20 pages /20 questions</td><td>Text, DOC files</td></tr>
<tr><td>ZenoCHAT</td><td>Not specified</td><td>20 questions</td><td>Text, Chat interface</td></tr>
</table>

The LLM that the AI tool depends on, limits of the free plan, data formats for interaction are considered to make a decision for the final selection. Between these AI tools, ChatGPT-3.5, Gemini AI and ChatPDF are selected for this research. ChatGPT-3.5 is considered due to its widely used LLM base and its substantial free plan while Gemini AI is considered as it is pointed out as one of the biggest rivals of the ChatGPT and its extensive free plan. Finally, ChatPDF is added to the research because of its capability to interact with direct pdf formatted document uploads.

This research has limitations that are related to the selected Generative AI tools and their restrictions as well as the research design including the limitations of the previous research selected to compare the results of AI interface. All these limitations are extensively discussed in the Results and Discussion section.

Results and Discussion

Articles are uploaded one by one, according to the format accepted by the Generative AI tools selected. ChatPDF interface enabled pdf formatted text uploads, so downloaded articles are uploaded easily. On the other hand, ChatGPT 3.5 and Gemini accepted only plain text, so the articles are transformed into text formatted documents using Automator 2.10 software. Moreover, due to the text size limitations documents are cut into two or three pieces and fed into the AI tools following an introduction prompt that basically describes the upload process and defines the expectations after giving the set of questions. Then, the answers are copied into an MS Excel file and processed for analysis. Although ChatPDF seemed more competent for the task due to its pdf formatted text interaction availability, it is dropped from the AI tools list due to unexpected challenges faced after five articles. These challenges are caused by its free plan allowance of only two document uploads per day and the instabilities faced while using the tool.

The answers received are processed on a table to match the same wording for each AI tool. After editing the answers, each box on the table is colored to show the accuracy of the answers in comparison with the answers of the referenced article (Ilter & Dikbaş, 2008). Coded colors and their meanings are shown on Table 2. According to these codes, between red represents an unmatching answer and green is the exact answer in comparison. Pale green is used to show altered answers which were unmatching first, but a correct answer is received when the question is revised and asked again. Yellow represents answers that have missing components, so they are partially correct, and blue shows answers where some additional information of choice is suggested by the AI as an answer.

Table 2. Color codes for answer comparison.

color code	provision	value
(red)	Unmatching answer	0
(yellow)	Not exactly but has in common	0,5
(pale green)	Corrected answer with revised question	1
(green)	Exact result	
(blue)	Exact result with additional components	

These color codes are turned into numerical values to determine the performance of each AI tool's answer to that specific article text. An unmatching answer coded as red is regarded as zero. While code yellow is regarded as half points (0,5), all green and blue codes are accepted as correct and regarded as '1'. Results of different AI tools in comparison are arranged in two different table groups. First group of tables is organized to include the meta-classification framework's 'Author', Content' and 'Research Style' factors defined in questions 1-11. However, Q1 'Number of authors', Q4 'Keywords' and Q9 'Definition of innovation" are not included in the table due to space constraints. A second set of tables represents the fourth factor 'Identified drivers and barriers of innovation'.

Table 3. Results for author, content and style (first page only due to space constraints).

		author		content				style	
Author(s)	AI Tool	author background	author country	research stream	level of analysis	stage of lifecycle	Definition of innovation?	sources of information	contribution of the artice
		Q2	Q3	Q5	Q6	Q7	Q8	Q10	Q11
Knuf (2000)	İlter & Dikbaş (2008)	A / O	USA	Inter-firm	Firm / Organization	Construction	N	Review	General insights
	ChatGPT 3.5	A. / M	N/A	N/A	Firm / Organization	N/A	N	Other emp. data	General insights
	ChatPDF	A. / M	N/A	Project Management	Firm / Organization	N/A	Y	Case study, Other emp. data	General insights
	Gemini	A. / M	N/A	Multi-project firm	Firm / Organization	N/A	N	Review, Case study	General insights
Park et.al. (2004)	İlter & Dikbaş (2008)	A / C	Singapore, UK	Project Ecology	Professionals	N/A	Y	Survey / interview	Model Building
	ChatGPT 3.5	A / C	Singapore, UK	Multi-project firm	Project	Several	Y	Survey / interview	Model Building
	ChatPDF	A / C	Singapore, UK	Project Management	Project	Construction	Y	Survey / interview	Model Building
	Gemini	A / C	Singapore	Multi-project firm	Project	Several	Y	Review	Model Building
Chan et.al. (2004)	İlter & Dikbaş (2008)	A / C	Hong Kong	Inter-firm	Project	Construction	N	Survey / interview	Statistical results
	ChatGPT 3.5	A / C	Hong Kong	Inter-firm	Project	N/A	N	Survey/int., Case study	General insights, Statistical results
	ChatPDF	A / C	Hong Kong	Inter-firm	Firm / Organization, Project	Several	Y	Survey/int., Case study	Statistical Results, Model Building
	Gemini	A / C	Hong Kong	Inter-firm	Firm / Organization	Several	N	Review, Survey / interview	Statistical results
Mitropoulos &Tatum (2000)	İlter & Dikbaş (2008)	P & A/C	USA	Contingency	Firm / Organization	Several	Y	Case study	Model Building
	ChatGPT 3.5	A / C	USA	Contingency	Firm / Organization	Several	Y	Case study	General insights
	ChatPDF	A / A	USA	Contingency	Firm / Organization	N/A	Y	Case study	General insights
	Gemini	A / C	N/A	Multi-project firm	Firm / Organization	Several	N	Case study	General insights
Ling et.al. (2007)	İlter & Dikbaş (2008)	A / C	Sing., Netherl., HK, Dubai	Project Management	Project, Client	N/A	N	Survey / interview	Statistical results
	ChatGPT 3.5	A / C	Sing., Netherl., HK, Dubai	Multi-project firm	Other	Construction	Y	Survey/int., Case study	General insights
	ChatPDF	A / C	Sing., Netherl., HK, Dubai	Project Management	Client	Construction	Y	Survey / interview	General insights
	Gemini	A / C	Hong Kong	Multi-project firm	Client	Construction	N	Survey / interview	Statistical results

Table 3 shows the first group of results showing meta-classification framework's factors of 'Author', Content' and 'Research Style'. For the first 5 articles ChatPDF's performance is at a breakeven point with ChatGPT while they are slightly ahead of Gemini AI, with 65% of accurate answers against 60%. Although the answers are not identical, this result is not surprising as the LLM used by ChatPDF is ChatGPT 3.5 itself. After the fifth article ChatPDF is not queried due to the reasons stated above.

Fine-tuning the questions by revising them in discussion with AI tools went on until the end of article 10. At the of these performance improvements, results show ChatGPT ahead with 63,75% compared to the score of Gemini with 60%. However, the results changed considerably for the ChatGPT when the second ten articles are queried. While Gemini's performance fell slightly to 56,25% ChatGPT's performance fell nearly 15% to 47,5%. With these results, at the end of 20 articles ChatGPT's performance score was 55,63% while Gemini AI scored 58,13% in total.

Another table is prepared for the results of AI tools' scores on the *drivers and barriers of innovation*, which is also in accordance with the original article that is being used to compare the performance. Similar to the first table prepared to compare the meta-classification framework's first three factors, these answers are also colored using same colors for coding given in Table 2. Nevertheless, content of this table demanded a few changes due to the interaction between the two group of columns on the table that were directly related to each other.

While the first two columns of the table were deserted for 'innovation drivers' and the 'means to establish drivers', following two columns were for 'innovation barriers' and 'means to overcome barriers'. As viable for any two concepts opposite to each other semantically, while presence of a notion can be a driver for innovation, lack of it normally causes a barrier. Thus these two sets of columns can simply be filled with supportive and unsupportive expressions of the same concept. On the other hand, the original table of drivers and barriers in the reference article was kept simple, which does not intend to include both the negative and positive expressions of the same notion on both sides of the table. Due to this simplicity, the original table avoids repetition and most of the concepts extracted from the articles are placed either on the barrier or the driver side depending on the approach of the inspected article, leaving many cells empty. However, when the generative AI tools are asked about these concepts one after another, they are quite capable of converting sentences to affirm or repulse expressions to fit in the form of the question. Therefore, the answers of the AI tools may fill in all the cells where the original table have gaps, or fill in the barriers part instead of drivers with a negative sentence, or vice versa.

The answers of the AI tools for the drivers and barriers questions are shown in Table 4. ChatPDF results are excluded as the limitations of the free plan of the AI tool did not enable to proceed its use in practice. In order to keep the integrity of the research and focus on the main aim of the study, the coding of the answers are changed considering all the answers both for drivers and barriers. For example, if a driver or barrier could not be identified by the AI tool in any of the questions, a 'Not Available' answer or shortly 'N/A' across a gap in the original table is not regarded as an 'Exact answer'(green) but considered as 'Not exactly but has in common'(yellow). Similarly, if an answer fills in a gap across the original table after conforming the original research's findings in any of the cells, that particular cell is awarded with color blue, which corresponds to 'Exact result with additional components'. When the numerical values designated to this answer scheme are considered, the coverage ratios of ChatGPT and Gemini are calculated as 81,25% and 83,75% respectively.

Based on our findings, the AI tools' performance in analyzing articles and extracting factors concerning author information, content, and research style yielded a relatively low average accuracy of 57%. Conversely, their proficiency in identifying factors associated with the drivers and barriers of innovation achieved a notably higher average accuracy of 82.5%. On the low side the AI tools could not detect some information easily noticeable for human eye. Some of the examples for such obvious information where the AI tools made frequent mistakes included number of authors, author background information and the keywords of the articles. In the initial ten articles, the researchers revised the questions in discussion with the Generative AI tools trying to create more clear queries, or add directive information about the format and position of the sought-after data. Despite multiple revisions to the questions, there was minimal impact on the accuracy of their responses. Throughout this process, potential factors contributing to discrepancies were identified, including conflicts arising from proper nouns and author name abbreviations, as well as challenges in detecting institutional information from article cover pages where many other additional data were present. The plain text format, that the pdf formatted articles are converted into are also considered liable from these mistakes. On the other hand, AI tools failure to detect the already listed keywords under the abstracts lied in their design. Despite efforts to refine the questioning by specifying the position of these terms, such as indicating that they commence with ‘Keywords:’ or ‘"CE Database subject headings:" as they are defined in ASCE articles, did not changed much about the results, AI tools showed a tendency to extract their own set of keywords from the entire article. Although this inclination towards comprehensive text processing initially contributed to their lower performance in the first set of questions, the same feature emerged as the primary factor behind their success rate in the analysis of drivers and barriers.

As the results indicate, generative AI demonstrates a notable capability to discern the context of articles, enabling it to effectively evaluate the discussions presented within and extract pertinent therein. One particularly impressive aspect is their capacity to analyze the cause-and-effect relationships embedded within these discussions. By identifying causal links and understanding the ramifications of various factors discussed, generative AI tools can provide valuable insights into the dynamics shaping the subject matter. This skill is invaluable in fields where understanding the underlying drivers and barriers is crucial for decision-making and strategy development. This proficiency underscores the potential of generative AI to not only comprehend the content of scholarly discourse but also to discern the underlying patterns and connections within the discussions. By delving into the nuanced interplay of ideas and arguments, generative AI holds promise for facilitating deeper insights into complex topics, thereby augmenting the efficiency and depth of scholarly research processes

Limitations of this research should be mentioned to conclude the results and discussion. First of all, there are increasing number of AI tools that are committed to analyze textual data. Generative AI tools selected for this research, ChatGPT and Gemini are leading examples from OpenAI and Google respectively, and many other AI tools in this track rely on them in the background such as ChatPDF. However, the algorithms behind different tools can make significant changes and AI tools which do not provide free plans currently can be prone to more deeper, accurate analysis, that may perform better and overcome the technical challenges faced extracting some of the meta-classification framework factors. Another research limitation appeared from to the article transformation process while converting pdf formatted documents to plain text. Depending on their journal’s format, articles had additional cover pages with

Table 4. Results for innovation driver and barriers (first page only due to space constraints).

Author(s)	AI Tool	innovation drivers		innovation barriers	
		drivers	means to establish drivers	barriers	means to overcome barriers
		Q12	Q13	Q14	Q15
Knuf (2000)	İlter & Dikbaş (2008)	lean production, knowledge management, continious learning	benchmarking		
	ChatGPT 3.5	N/A	N/A	N/A	N/A
	Gemini	N/A	N/A	Limitations of internal information sources	Networking with other companies pursuing similar goals
Park et.al. (2004)	İlter & Dikbaş (2008)	project performance, organizational climate,	PM-driven motivation, PM's championing behavior, team member-driven motivation		
	ChatGPT 3.5	PM-driven motivation, team member-driven motivation	PM's championing behavior, organizational climate for innovation	Organizational climate for innovation, barriers to innovation	Restructuring environment to facilitate innovation on site
	Gemini	Project perform. gap, organizational climate, PM championing behavior	Acknowledgement and reward, delegate decision authority, training, support, autonomy	Lack of resources, decision authority for PMs, Resistance to change	authority to PMs, Address resistance through communication and education
Chan et.al. (2004)	İlter & Dikbaş (2008)			poor communication and trust	partnering
	ChatGPT 3.5	Commitment, clear communication, trust	Establishing effective conflict resolution, willingness to share resources, clear definition of responsibilities	Lack of commitment, poor communication, lack of trust	Building commitment, improving communication, fostering trust
	Gemini	N/A	N/A	N/A	N/A
Mitropoulos &Tatum (2000)	İlter & Dikbaş (2008)	competitive advantage, process problems, technological opportunity, and institutional requirements	CAD, ICT		
	ChatGPT 3.5	Competitive advantage, process problems, technological opportunity	enhancing potential for competitive advantage, and increasing technological opportunity.	High costs, Lack of knowledge, Resistance to change, Tech&financerisks, Ext. requirements	initiate change, and enhancing potential for competitive advantage.
	Gemini	Competitive Adv., Process Problems, Techn. Opportunity, Ext. Requirements	Increase ext. requirements, potential for competitive adv., technological opportunity	N/A	N/A
Ling et.al. (2007)	İlter & Dikbaş (2008)	client			
	ChatGPT 3.5	Technical difficulties in the project	N/A	Lack of team spirit, coordination problems, contractual issues, regulatory constraints	separate implementation teams, establish coordination and monitoring mechanisms
	Gemini	N/A	N/A	Lack of technical expertise by client	Increase client technical capabilities
Dikmen et.al. (2005)	İlter & Dikbaş (2008)	Customer orientation, culture, key individuals, financial resources		economic, political, legal, and sociocultural conditions; poor organizational learning.	
	ChatGPT 3.5	political conditions, economic factors, legal issues, socio-cultural aspects.	N/A	Politic, economic, legal issues, targets, strategies, and sources of innovation.	customer/supplier relations, strat. alliancing, HRM, KM/IT strategy, benchmarking, R&D
	Gemini	New markets, profitability, customer satisfaction	Strategic alliances, Environmental scanning - HR development, KM	Political instability, Lack of finance, Poor KM, Project-based nature of the industry, demand	Effective PM, Strong company culture, R&D - Improved learning
Bossink (2002)	İlter & Dikbaş (2008)	environmental pressure, tech. capability, knowledge exchange, boundary spanning			
	ChatGPT 3.5	Environmental pressure, tech.capability, knowledge exchange, and boundary spanning	collaboration, integration of design and build activities and involvement of clients	N/A	N/A
	Gemini	Environmental pressure, Tech. capability, Knowledge exchange, Boundary spanning	Government policies, R&D Investment, Collaboration, integration	Lack of demand for sustainability, Limited risk tolerance/innov. management experience	Government incentives for sustainability, Building knowledge and innovation experience
Chan et.al. (2003)	İlter & Dikbaş (2008)	partnering			
	ChatGPT 3.5	Commercial pressure, uneven commitment, lack of partnering experience	balanced commerce and partnering, openness, trust, communication, commitment	uneven commitment among participants	fostering openness, trust, communication, and commitment
	Gemini	N/A	N/A	pressure to compromise partnering, Uneven project commitment, No partnering experience	N/A
Na et.al. (2006)	İlter & Dikbaş (2008)	profit incentives, social desirability of higher construction productivity and quality.			
	ChatGPT 3.5	foreign direct investment (FDI), collaboration with suppliers and research institutions	Profit incentives, strategic alliances, joint ventures	excessive social pressures, monopolistic characteristics, high entry barriers	Moderating profit initiatives, reducing social pressures, fostering strategic learning
	Gemini	Profit Motive, Social Pressure for improved construction quality & productivity	government policies, review social expectations for innovation efforts	Fragmented industry, Std.contracts & procure. methods, reliance on FDI for innovation	collaboration, domestic R&D, foreign and local contractors' balance

journal information, or information on each page such as topics of the article, topic of the journal, authors etc. which were also converted with the article's text body, that may have caused some challenges while extracting relevant information. AI tools have limitations about the length of text that can be uploaded, which is encompassed by uploading articles in sections. Last but not least, it is widely debated that the format of the questions posed to the AI tools have a higher impact on the answer received. Although the questions are revised many times according to the reviewed literature, constructive directives of specialists interviewed, and feedback from the AI tools themselves, prompting stands for being an upcoming profession in the near future and state of art prompts can easily change the performance of such analysis. Finally, the article that is taken as the reference matter of this research has limitations itself that should also be taken into consideration while assessing the performance measures.

Conclusion

In conclusion, this study evaluated the performance of generative AI tools, namely ChatGPT and Gemini, in analyzing articles and extracting factors related to author information, content, research style, and the drivers and barriers of innovation. While the AI tools demonstrated a relatively low average accuracy of 57% in analyzing these factors, their proficiency improved significantly when identifying factors associated with innovation drivers and barriers, achieving an average accuracy of 82.5%. However, limitations were observed, particularly in detecting certain information readily noticeable to the human eye, such as the number of authors, author background information, and article keywords. Despite efforts to refine the questioning and specify the position of terms, the AI tools tended to extract their own set of keywords from the entire article.

Notably, generative AI tools showcased a remarkable capability to discern the context of articles, evaluate discussions, and identify cause-and-effect relationships within the text. This proficiency holds promise for facilitating deeper insights into complex topics and augmenting the efficiency and depth of scholarly research processes.

However, it's important to acknowledge several limitations in our study. The algorithms behind different AI tools may vary significantly, potentially impacting their performance. Additionally, challenges were encountered during the article transformation process from PDF to plain text, and limitations exist regarding the length of text that can be uploaded to AI tools. Furthermore, the format of questions posed to AI tools may influence the accuracy of their responses. Finally, it's essential to consider the limitations of the reference article used in our research.

Looking ahead, future research should address these limitations and explore the potential of generative AI tools further. By refining methodologies, addressing technical challenges, and leveraging advancements in AI technology, we can enhance the accuracy and reliability of AI-driven analyses in scholarly research.

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References

Ceylan, S. (2021). Artificial intelligence in architecture: An educational perspective. *13th International Conference on Computer Supported Education (CSEDU 2021)*, 100–107. https://doi.org/10.5220/0010444501000107

Davenport, T. H., & Alavi, M. (2023). *How to train generative AI using your company's data*. *Harvard Business Review*. July 06. https://hbr.org/2023/07/how-to-train-generative-ai-using-your-companys-data?utm_medium=paidsearch&utm_source=google&utm_campaign=intlcontent_tech&utm_term=Non-Brand&tpcc=intlcontent_tech&gad_source=1&gclid=Cj0KCQiAoKeuBhCoARIsAB4WxteskA6aeAHdaC64p21rr2-Kuk_zm7F9TvdBJkcgvSdpWL3igRtpficaArxXEALw_wcB

Dickinson, M., Cooper, R., McDermott, P., & Eaton, D. (2006). An analysis of construction innovation literature. *Third International Built and Human Environment Research Week*.

Emaminejad, N., North, A. M., & Akhavian, R. (n.d.). Trust in AI and implications for AEC research: A literature analysis. In *Computing in Civil Engineering 2021* (pp. 295–303). https://doi.org/10.1061/9780784483893.037

Ghimire, P., Kim, K., & Acharya, M. (2024). Opportunities and challenges of generative AI in construction industry: Focusing on adoption of text-based models. *Buildings*, *14*(1), 220. https://doi.org/10.3390/BUILDINGS14010220

Ilter, A. T., & Dikbas, H. A. (2008). An analysis of drivers and barriers of construction innovation. In Y. Nielsen (Ed.), *Innovation in Architecture, Engineering and Construction (AEC)*.

Kubow, A. (n.d.). *Prompt engineering tutorial – Master ChatGPT and LLM responses - YouTube*. Retrieved April 28, 2024, from https://www.youtube.com/watch?v=_ZvnD73m40o

LinkedIn Learning. (2024). *Workplace learning report 2024*. https://learning.linkedin.com/resources/workplace-learning-report?trk=bl-po&veh=AI-learning-day

Pan, Y., & Zhang, L. (2021). Roles of artificial intelligence in construction engineering and management: A critical review and future trends. *Automation in Construction*, *122*, 103517. https://doi.org/10.1016/j.autcon.2020.103517

Pan, Y., & Zhang, L. (2023). Integrating BIM and AI for smart construction management: Current status and future directions. *Archives of Computational Methods in Engineering*, *30*, 1081–1110. https://doi.org/10.1007/s11831-022-09830-8

Redwood, J., Thelning, S., Elmualim, A., & Pullen, S. (2017). The proliferation of ICT and digital technology systems and their influence on the dynamic capabilities of construction firms. *Procedia Engineering*, *180*, 804–811. https://doi.org/10.1016/J.PROENG.2017.04.241

Rokooei, S., Alvanchi, A., Shojaei, A., & Ford, G. (2023). Developing an impact model in construction companies during pandemics. *Journal of Engineering, Project, and Production Management*, *2023*(2), 159–169. https://doi.org/10.32738/JEPPM-2023-0016

Schryen, G., Marrone, M., & Yang, J. (2024). Adopting generative AI for literature reviews: An epistemological perspective. *57th Hawaii International Conference on System Sciences*. https://scholarspace.manoa.hawaii.edu/items/3165a8d1-7ed2-4876-b626-ac5b0985f2bc

Vakilzadeh, A., Pourahmad Ghalejoogh, S., & Hatami, M. (2023). Evaluating the potential of large language model AI as project management assistants: A comparative simulation to evaluate GPT-3.5, GPT-4, and Google-Bard ability to pass the PMI's PMP test. *SSRN Electronic Journal*. https://doi.org/10.2139/SSRN.4568800

A Literature Review on Digital Twin Acceptance and Adoption in the Construction Industry: A Roadmap for Devising an Information Technology Acceptance Model

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Abstract

The concept of digital twin (DT) has been attracting interest as a holistic information technology to address certain problems encountered mainly by manufacturing industries. Digital twins are virtual/digitalized replicas of physical processes, products or systems, created for simulating, foreseeing and optimizing their performance. In this respect, their potential extends to the construction industry, which has long been suffering digitalization problems related to the acceptance of new technologies. Understanding potential barriers to the acceptance and adoption of digital twins in construction is crucial, and these factors should be analyzed carefully to mitigate these challenges. This study aims to present a literature review on digital twin acceptance and adoption in the construction industry. After a comprehensive search, a limited number of relevant studies could be found, and it is proposed that insights from acceptance and adoption research on building information modelling (BIM), a technology similar in nature to digital twins, can help propose a novel digital twin acceptance model for the construction industry. A systematic literature review yielded candidate models which are mostly based on the technology acceptance model (TAM), and a roadmap for devising a digital twin acceptance model is presented by making use of these models.

Keywords: *building information modelling, construction industry, digital twins, literature review, technology acceptance model, technology adoption.*

Introduction

The ever-growing building and infrastructure needs of societies necessitate undertaking construction projects on larger scales for construction companies and contractors. Given the unique nature of each individual construction project, which involves large numbers of interacting tasks, the complexity increases progressively. Increased complexity in large-scale construction projects, therefore, brings about significant challenges in terms of time, budget and quality constraints, and the construction industry has been perpetually striving to propose solutions to these challenges. The construction industry still has a huge potential to be tapped into in terms of streamlining the tasks involved for increasing time and cost efficiency, and new technologies and methodologies are continuously explored to this end.

As the concept of data-driven analytics and transforming data via concepts such as Internet of Things (IoT) and big data into action is becoming more prominent in the construction industry, considerable effort is being poured into better utilization of these tools and methods at disposal (Ammar et al., 2022). In addition, artificial intelligence (AI) along with machine learning and deep learning provides opportunities for more sophisticated uses of collected or available data to introduce better accuracy and decision-making into construction practices. All these developments are being harnessed in many industries, including the construction industry, albeit to a limited extent. Long-lasting digitalization problems, such as outdated systems and technology integration, lack of technology standardization, resistance to adopt new technologies, and skills gap, hinder the acceptance and adoption of new information technologies in the industry. Therefore, it is imperative in this era of rapid technological developments, some of which are outlined here, that the means for the construction industry to capitalize on these developments be explored, and the concept of digital twin has emerged as a robust solution candidate to do so in order to address certain fundamental challenges experienced in the construction industry.

Fundamentally, a digital twin is a simulation-based concept acting as a virtual digital replica or copy of a physical product or process, which is used for planning, simulating, foreseeing and optimizing performance (Opoku et al., 2021). Digital twins accomplish these tasks through the collection of real-time data, which allows predictive maintenance and brings about informed decision-making (Khajavi et al., 2019). Digital twins leverage a wide variety of technological developments and methods, such as Internet of Things (IoT), data analytics, cloud computing, AI, machine learning and many more (Sacks et al., 2020). In essence, digital twins serve as a vital link between the physical and digital universes to offer many industries new ways to manage and optimize their processes and products.

Digital twins may open new pathways in the construction industry by integrating its brand-new methods and tools with the existing ones, thus overcoming the inherent problems in current practices. Building Information Modelling (BIM) implementations, for one, can be integrated with digital twins along with lean thinking and AI to achieve efficient construction management practices, and this would be possible thanks to the significant level of similarity between BIM models and digital twins. Capabilities of BIM models can be expanded by real-time data and predictive analyses provided by creating corresponding digital twins (Khajavi et al., 2019). It is also possible with digital twins to optimize workflows in construction projects to reduce waste and energy consumption, and enhance resource utilization (Pan & Zhang, 2021), with the robust methods of digital twins for collecting and using comprehensive and accurate real-time data. Data-related capabilities of digital twins can also provide improvements for informed decision-making at all stages of construction projects (Boje et al., 2020).

Despite their promise to improve construction practices, digital twins have not reached the state of widespread use within the construction industry. Among the key challenges resulting in a delayed adoption of digital twins, resistance to adopt digital twins in the construction industry as a novel information technology comes first (Opoku et al., 2021; Agarwal et al., 2016; Leviäkangas et al., 2017). Therefore, the acceptance and adoption of digital twins as a novel information technology (IS) in the industry should be studied in depth to identify potential barriers and to analyze them in detail for devising mitigation methodologies.

Information technology usage is, in a sense, a demonstration of the acceptance of the technology by its potential users and proves to be a basis for research towards examining the determinants of IT acceptance and usage. With this principle in mind, many models and approaches have been developed. As a prominent example of such efforts, technology acceptance model (TAM) was introduced by Davis (1989) to adapt the theory of reasoned action (TRA) by Ajzen (1980) and the theory of planned behavior (TPB) by Ajzen (1985) to model user acceptance of information systems. TAM is aimed at providing a theoretically justified explanation of the determinants of information technology acceptance, which can also account for user behavior for different end-user technologies among diverse user populations. TAM assumes that the behavioral intention of a user is determined by a performance expectancy construct known as perceived usefulness, which is defined as the extent to which an individual believes that using the technology will enhance their job performance, and by an effort expectancy construct known as perceived ease of use, which is defined as the extent to which an individual believes that using the technology will be easy. Successive technology acceptance models in the literature, such as the Unified Theory of Acceptance and Use of Technology (UTAUT) by Venkatesh et al. (2003), strived to augment their predecessors by adding constructs to their models pertaining to social influences, facilitating conditions, attitude toward using technology, self-efficacy, anxiety, and behavioral intention to use. In addition, communication theories such as innovation diffusion theory (IDT) by Rogers (1995) are also considered within the context of information technology acceptance research in order to devise information technology acceptance models and methods. Most of these methods and models are utilized by collecting data from potential users via surveys with concise scale items constructed to have a correspondence to the aforementioned constructs. IT acceptance models have been used for the acceptance of many technologies that are currently in use in a wide variety of industries, and, in a similar vein, research efforts in this field can be utilized for the construction industry.

This study aims to systematically review the academic literature on the acceptance and adoption of digital twin technology within the context of information technology acceptance models and propose contributions to fill the gap. This way, it is intended to guide both researchers and practitioners in the construction industry to explore more efficient methodologies to introduce digital twins into their research and implementations in their organizations.

Methodology and Findings

This study adopts the "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" (PRISMA) guidelines to review the literature, in order to ensure accuracy, reliability and clarity in the reporting process (Moher et al., 2009). In the identification phase of the literature review for digital twin adoption and acceptance, the literature search was conducted on Scopus and Web of Science (WoS) databases using the following terms:

The searches on both databases covered only journal articles, conference papers, and reviews written in English, which are related to the construction industry. While selecting the keywords for the field of technology acceptance and adoption, the IS acceptance theories or models that are more common in the literature, namely technology acceptance model (TAM), diffusion of information theory (DOI) or information diffusion theory (IDT), theory of planned behaviour (TPB), theory of reasoned action (TRA), task-technology fit model (TTF) and the unified theory of acceptance and use of technology (UTAUT), are sought (Taherdoost, 2018). After the identification phase, the results collected from both searches are combined and duplicates are removed in the screening phase. Then, the texts in which DT is not the main topic or in which DT adoption or acceptance is not discussed are excluded. In the eligibility phase, 36 papers were selected to be included in this study. However, only two out of 36 papers were found to be discussing DT adoption and acceptance within the scope of IS acceptance theories, marking the scarcity of studies to this end (see Figure 1).

Table 1. Structure of the query string used in Scopus for DT-related papers.

Descriptions and Fields	**Operators and Keywords Used**
Search elements	TITLE-ABS-KEY
Digital Twin	(*"digital twin"* OR *"digital twins")*
Operator	AND
Construction Industry	(*"construction"* OR *"building"* OR *"built environment"* OR *"AEC"* OR *"AECO"* OR *"AECOFM"* OR *"asset management"* OR *"facility management"* OR *"operation and maintenance"* OR *"management"* OR *"construction management"*)
Operator	AND
Technology Acceptance and Adoption	(*"acceptance"* OR *"adoption"* OR *"technology acceptance"* OR *"TAM"* OR *“diffusion of innovation theory”* OR *“DOI”* OR *“innovation diffusion theory”* OR *“IDT”* or *“task-technology fit”* OR *“TTF”* OR *"theory of planned behavior"* OR *"TPB"* OR *"theory of reasoned action"* OR *"TRA"* OR *“UTAUT”* OR *"unified theory of acceptance and use of technology"*)

Out of these two papers, the work by Wong et al. (2022) proposes a conceptualization of the Task-Technology Fit (TTF) acceptance model, which is intended for determining the relationship between the task characteristics in building maintenance tasks and technology characteristics to increase performance and achieve the utilization of digital twins. The selected task characteristics, namely correctiveness, preventiveness, predictiveness, and prescriptiveness, are matched with digital twin characteristics, namely real-time data and monitoring, overall anomaly detection, augmented reality to show failures, prediction of state of asset and costs, and simulation of scenarios, to evaluate the fit of the digital twin technology with the maintenance task under scrutiny. To this end, a TTF Evaluation Template and a TTF-Performance Impact Matrix are created to observe these relationships. The resulting model, then, could be utilized to determine the suitability of digital twin technology for completing building maintenance tasks.

Table 2. Structure of the query string used in Web of Science for DT-related papers.

Descriptions and Fields	**Operators and Keywords Used**
Search elements	TI (title) OR AB (abstract) OR AK (author keywords)
Digital Twin	(*"digital twin"* OR *"digital twins")*
Operator	AND
Construction Industry	(*"construction"* OR *"building"* OR *"built environment"* OR *"AEC"* OR *"AECO"* OR *"AECOFM"* OR *"asset management"* OR *"facility management"* OR *"operation and maintenance"* OR *"management"* OR *"construction management"*)
Operator	AND
Technology Acceptance and Adoption	(*"acceptance"* OR *"adoption"* OR *"technology acceptance"* OR *"TAM"* OR *“diffusion of innovation theory”* OR *“DOI”* OR *“innovation diffusion theory”* OR *“IDT”* or *“task-technology fit”* OR *“TTF”* OR *"theory of planned behavior"* OR *"TPB"* OR *"theory of reasoned action"* OR *"TRA"* OR *“UTAUT”* OR *"unified theory of acceptance and use of technology"*)

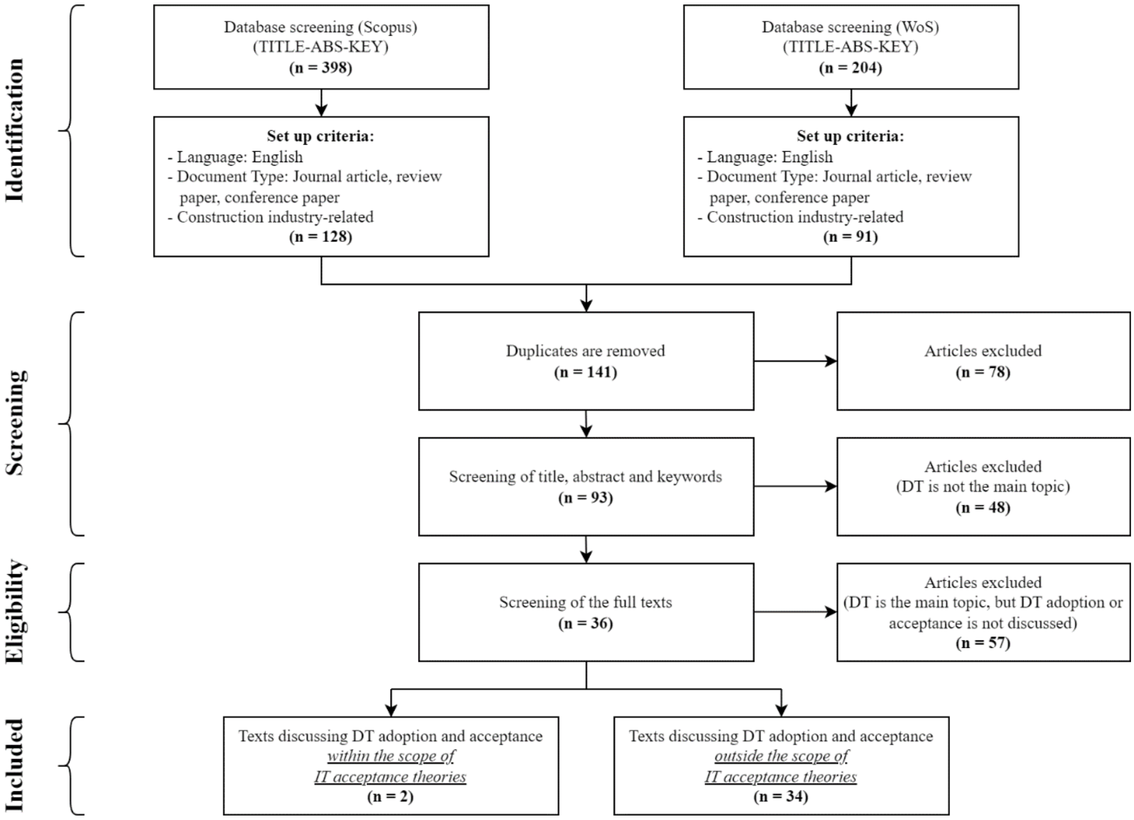

Figure 1: The PRISMA flow diagram for DT adoption and acceptance literature review (adapted from [Moher et al., 2009]).

The other study by Sepasgozar et al. (2021) conducts a literature review on the current technology acceptance model (TAM) in the field of mixed reality and digital twin (MRDT) to devise an extended TAM model for MRDT adoption. The collected data from the literature review are then used as input in statistical analyses (Cronbach α) to test the average reliability of the hypothetical relationships between different TAM factors, such as perceived ease of use, perceived usefulness, behavioural intention, and attitude. The study concluded that subjective norm, social influence, perceived ease of use, perceived security, perceived enjoyment, satisfaction, perceived usefulness, attitude, and behavioural intention are the constructs of the extended TAM for predicting MRDT adoption in the AECO industry, marking the factors to be considered in the construction of similar technology acceptance models.

Although these two studies provide insight into prospective digital twin models which could be utilized for broader implementation of digital twins in the construction industry, the research efforts towards this purpose can benefit from a more diverse and populous selection of implementation examples. This way, acceptance models which are more applicable or representative can be determined. These results were not unexpected, given that digital twin implementations are currently recording a slow progress in the construction industry, and there is no general inclination in the industry towards digital twin acceptance at an organizational level, which would necessitate the creation of a technology acceptance model. Upon careful examination of the results of the literature review efforts outlined here, it was observed that digital twins are increasingly considered to be the natural successor of building information modelling (BIM), which is another information technology extensively used in the construction industry for end-to-end project management (Honghong et al., 2023; Deng et al., 2021). The similarities in their capabilities, the challenges they strive to address and suffer in their organization-wide implementations are extensive, and there exists several acceptance and adoption studies related to BIM within the context of IT acceptance. It is suggested, therefore, that searching the literature for technology acceptance models intended for BIM may prove beneficial for devising a similar model for digital twins.

In a second literature search for finding texts to serve this purpose, Scopus and Web of Science (WoS) databases are used with the same search terms as the ones used for the previous cycle of literature search, after changing the keywords related to digital twins with those related to BIM, and by removing the separate keywords of "acceptance" and "adoption", since these terms resulted in query returns not related to information technology acceptance models. At the end of the screening and eligibility processes (see Figure 2), 78 papers related to BIM adoption and acceptance within the scope of IT acceptance theories were found. Upon the examination of the 78 papers received at the end of the PRISMA flow, it was observed that studies employing TAM and DOI make up the majority of these papers, but other models and methods such as TTF and UTAUT, in addition to hybrid models, also have been utilized by researchers to investigate BIM adoption and acceptance. Given the variety and the abundance of studies on this topic, it is possible to create a roadmap to devise an IT acceptance model for digital twins in the construction industry.

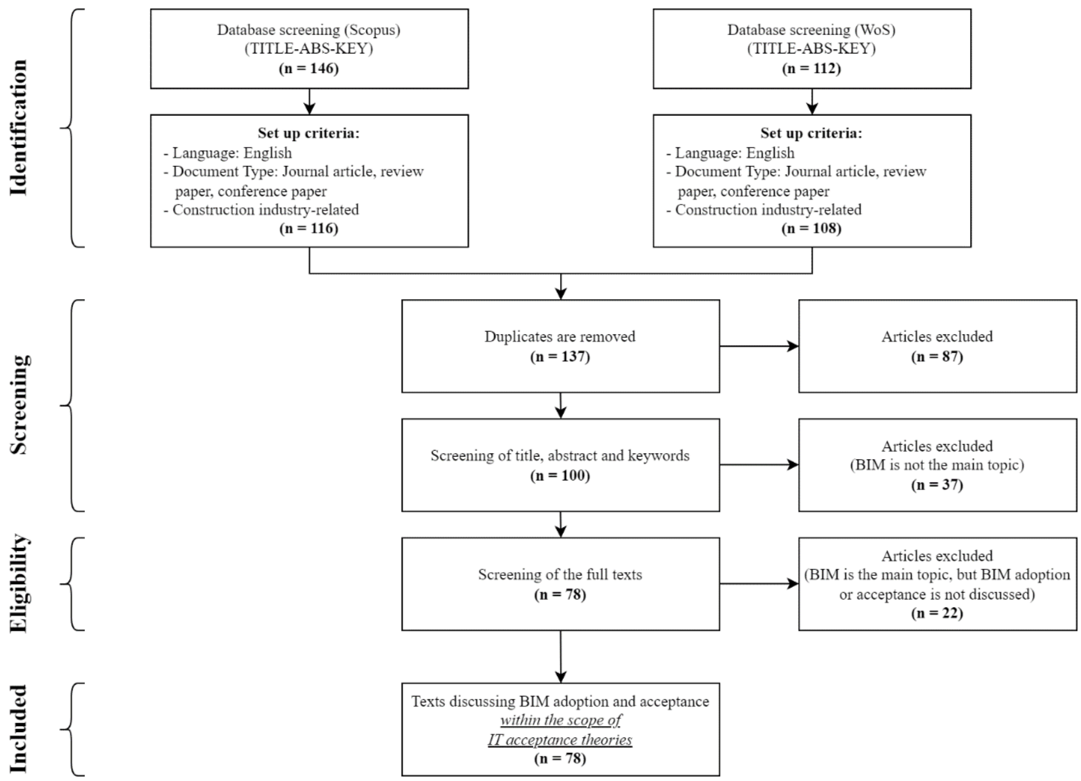

Figure 2: The PRISMA flow diagram for BIM adoption and acceptance literature review (adapted from [Moher et al., 2009]).

Proposed Roadmap and Conclusion

This study presents a systematic literature review on the acceptance and adoption of digital twins and BIM in the construction industry, with the purpose of proposing a roadmap to devise an IT acceptance model for digital twins. Since IT acceptance studies on digital twins were found to be scarce, studies on the acceptance of BIM as another similar information technology may prove to be a reliable knowledge base for proposing a roadmap. The first step of the roadmap is to classify the studies identified after a systematic review of the relevant literature according to the IT acceptance theories or models upon which their models are constructed. Then, the constructs used for categorizing the scales to collect user responses can be grouped according to the frequency of their use, followed by the identification of the most preferred scale items. These selections can be guided by examining the statistical analyses conducted for unfolding the interactions among these constructs and scales to further strengthen the soundness of the selection process. Finally, the models can be formed by combining these selections and then calibrated so that they follow the principles of the models and methods they are based on, and the implementation specifications can be determined. The outlined roadmap flow can be depicted as shown in Figure 5. Future studies may include the detailed breakdown of the proposed roadmap steps to enhance the correspondence of the devised models to IT acceptance literature, and the customization of the overall roadmap for implementation with different IT acceptance models and methods.

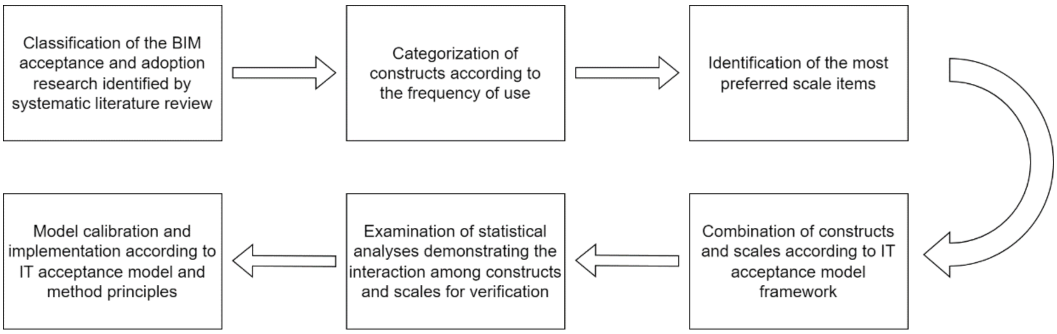

Figure 1: Proposed roadmap for devising an IT acceptance model for digital twins.

References

Agarwal, R., Chandrasekaran, S., & Sridhar, M. (2016). Imagining construction's digital future. *McKinsey & Company*, *24*(06).

Ajzen, I. (1985). From intentions to actions: A theory of planned behavior. In *Action control: From cognition to behavior* (pp. 11-39). Berlin, Heidelberg: Springer Berlin Heidelberg.

Ajzen, I. (1991). The theory of planned behavior. *Organizational Behavior and Human Decision Processes*, *50*(2), 179-211.

Ammar, A., Nassereddine, H., AbdulBaky, N., AbouKansour, A., Tannoury, J., Urban, H., & Schranz, C. (2022). Digital twins in the construction industry: a perspective of practitioners and building authority. *Frontiers in Built Environment*, *8,* 834671.

Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y. (2020). Towards a semantic construction digital twin: Directions for future research. *Automation in Construction*, *114*, 103179.

Davis, F. D. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. *MIS quarterly*, 319-340.

Deng, M., Menassa, C. C., & Kamat, V. R. (2021). From BIM to digital twins: A systematic review of the evolution of intelligent building representations in the AEC-FM industry. *Journal of Information Technology in Construction*, *26*.

Grieves, M., & Vickers, J. (2017). Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems. *Transdisciplinary perspectives on complex systems: New findings and approaches*, 85-113.

Honghong, S., Gang, Y., Haijiang, L., Tian, Z., & Annan, J. (2023). Digital twin enhanced BIM to shape full life cycle digital transformation for bridge engineering. *Automation in Construction*, *147,* 104736.

Khajavi, S. H., Motlagh, N. H., Jaribion, A., Werner, L. C., & Holmström, J. (2019). Digital twin: Vision, benefits, boundaries, and creation for buildings. *IEEE Access*, *7,* 147406-147419.

Leviäkangas, P., Paik, S. M., & Moon, S. (2017). Keeping up with the pace of digitization: The case of the Australian construction industry. *Technology in Society*, *50*, 33-43.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., & PRISMA Group*, T. (2009). Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *Annals of internal medicine*, *151*(4), 264-269.

Opoku, D. G. J., Perera, S., Osei-Kyei, R., & Rashidi, M. (2021). Digital twin application in the construction industry: A literature review. *Journal of Building Engineering, 40,* 102726.

Pan, Y., & Zhang, L. (2021). Roles of artificial intelligence in construction engineering and management: A critical review and future trends. *Automation in Construction*, *122*, 103517.

Rogers, E. M., Singhal, A., & Quinlan, M. M. (2014). Diffusion of innovations. In *An integrated approach to communication theory and research* (pp. 432-448). Routledge.

Sacks, R., Brilakis, I., Pikas, E., Xie, H. S., & Girolami, M. (2020). Construction with digital twin information systems. *Data-Centric Engineering*, *1*, e14.

Sepasgozar, S. M., Ghobadi, M., Shirowzhan, S., Edwards, D. J., & Delzendeh, E. (2021). Metrics development and modelling the mixed reality and digital twin adoption in the context of Industry 4.0. *Engineering, Construction and Architectural Management*, *28*(5), 1355-1376.

Taherdoost, H. (2018). A review of technology acceptance and adoption models and theories. *Procedia manufacturing*, *22*, 960-967.

Venkatesh, V., Morris, M. G., Davis, G. B., & Davis, F. D. (2003). User acceptance of information technology: Toward a unified view. *MIS quarterly,* 425-478.

Wong, J., Hoong, P., Teo, E., & Lin, A. (2022). Digital twin: A conceptualization of the task-technology fit for individual users in the building maintenance sector. In *IOP Conference Series: Earth and Environmental Science, 1101*(9), (pp. 092041). IOP Publishing.

Digital Twins for Knowledge Management During Earthquake Emergency

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Abstract

The chaotic emergency environment can create obstacles that may complicate prompt and effective responses for a resilient emergency management. The provision of vital information related to health services, shelter, nutrition, and availability of infrastructure is of utmost importance. In the context of earthquake emergency, Knowledge Management (KM) encompasses various techniques and approaches for acquiring, storing, generating, assessing, and sharing knowledge for efficient and effective mobility of people, goods, and services. Digital Twins (DT) can serve as a platform for KM, addressing challenges in earthquake emergency action plans and facilitating information sharing during critical hours and in the aftermath of disasters, ensuring timely and informed decisions for the survival of victims. This paper presents an Earthquake Emergency Knowledge Management framework through DT, based on expert judgment, and the scientometric analysis and mapping to identify gaps in existing KM methods. The proposed conceptual framework aims to improve response time and facilitate KM during an earthquake emergency to meet the primary needs of victims for survival. However, it's important to recognize potential limitations, such as challenges in resource-constrained settings or areas lacking digital infrastructure. Future studies may further focus on the secondary emergency requirements for the days following the earthquake, addressing not only survival but also recovery needs.

Keywords: *digital twins, earthquake, emergency, knowledge management*

Introduction

Each year, disasters impact people in all over the world, with earthquakes ranking among the most destructive in terms of human recovery (Jha et al., 2021). The absence of effective post-earthquake Emergency Management (EM) plans or the sharing of knowledge regarding the needs of victims with relevant teams/authorities highlights the importance of Knowledge Management (KM) during emergencies. EM involves a systematic approach that encompasses a variety of activities such as risk assessment, planning, resource allocation, communication and coordination of response efforts and stakeholders from a variety of sectors, including government agencies, non-governmental organizations, healthcare providers, law enforcement, and the private sector to reduce the impact of adverse events on individuals, communities and infrastructure. (Goode et al., 2016). Rapid and reliable KM in EM positively influences emergency response efforts (Dorasamy et al., 2013) and aids in supporting public health during humanitarian crises (Boshara et al., 2020). KM is a multifaceted concept that encompasses the processes and practices to create, capture, evaluate, store, and disseminate knowledge (Gao & Bernard, 2017).

Actors such as humanitarian aid organizations are the key enablers for delivery of victims' needs and logistics to the affected fields. However, they usually take necessary action without having a reliable information in their hands (Pedraza-Martinez et al., 2013). Decision-making poses a challenge due to the dynamic nature of the situation and the limited availability of information. In the era of digitalization, the abundance of accessible data continues to grow exponentially, presenting challenges in data management.

Digital Twins (DT), a concept initially defined by Michael Grieves in 2002, represent virtual information constructs that comprehensively describe physical products (Grieves, M., & Vickers, J., 2016). DT may play crucial role to enable more data-centric and effective management of the knowledge related to needs of victims. Development of KM applications and systems is important for creating efficient information sharing systems among stakeholders for response and recovery efforts in EM (Othman and Beydoun, 2016). Digital Twins (DT), which allow organizations to monitor, analyze and simulate the performance of physical assets or systems in real time, hold potential for Knowledge Management (KM) in EM by enabling better decision-making and predictive operations (Wang, 2021; Cooper et al., 2022).

The conceptual framework that is proposed in this paper is designed to address post-earthquake KM through DT, specifically targeting the immediate needs of victims within the first three days following an earthquake. In the following sections firstly the research background is outlined and then the presentation of the conceptual framework for KM in Emergency Earthquake Management (EEM) using DT is proposed. The paper concludes by examining both the limitations and potentials of the proposed framework.

Research Background

DT, which allow organizations to monitor, analyze and simulate the performance of physical assets or systems in real time, hold potential for KM in EM by enabling better decision-making and predictive operations (Wang, 2021; Cooper et al., 2022). DT improve situation assessment, coordination, and resource allocation in emergency scenarios by integrating various data sources and leveraging technologies such as Artificial Intelligence (AI) and big data analytics. DT is effective in improving operational processes, reducing downtime, and increasing overall efficiency (Židek et al., 2020; Egorov et al., 2021). In an emergency scenario, through DT, response plans can be optimized, modeling such as lists of needs and evacuation scenarios can be made from people who are victims of an emergency or disaster (Shaharuddin et al., 2022; Ahn & Kim, 2023).

The Conceptual Framework for KM through DT in emergencies refers to the application of DT technology in managing information in emergencies. As per the proposed framework, addressing challenges in post-earthquake action plans and ensuring efficient information sharing can be achieved through the full integration of DT, KM, and Emergency Management (EM). This integration can enhance collaboration and communication among various stakeholders involved in emergency response, including suppliers, manufacturers, logistics providers, and government agencies. By leveraging this integration, stakeholders can effectively meet the needs of victims in terms of health, water, shelter, food, and infrastructure following an emergency or disaster.

This paper aims to answer a fundamental question and related issues as listed below:

RQ. How can DT contribute to KM during earthquake emergency?

SRQ1. What are the challenges and potentials of DT in post-Earthquake Emergency Management (EEM)?
SRQ2. How can KM be implemented in responding the primary needs via DT after earthquake?
SRQ3. What are the limitations of the proposed conceptual framework?
SRQ4. What potential contributions does the proposed conceptual framework offer to future DT research?

Ensuring data quality, reliability, security and management can be a significant challenge, especially in a disaster scenario involving multiple stakeholders and data sources. The main aim of this paper is to propose a conceptual framework for KM via DT to be used during earthquake emergency times. The proposed framework suggests DT as a platform to acquire, process and share the information/knowledge with the responders effectively during earthquake emergency. The system will continuously be updated with the real-time data feed for improving resilience through EM.

Proposed Conceptual Framework

DT can serve as a platform (PaaS) to collect information about vital needs of victims (healthcare, nutrition, shelter, infrastructure) from several sources such as humanitarian aid organizations and public. Collected information can be shared with governmental organizations other suppliers via DT either. Within the framework of KM, DT can perform tasks such as data collection, data engineering, data storage, and data sharing. In this context, DT technology enables collaboration, data analysis, and decision-making during an emergency. In the proposed conceptual framework shown in Figure 1, the RAA model approach which highlights the Resources, Actors, and Activities in earthquake emergency. According to RAA Model, requests for main needs such as health, shelter, infrastructure, water, and food constitutes "Resources". Resources are received from those in need through sensors, Internet of Things (IoT) devices, and social media in EM in the real world. Resources are determined according to interviews with experts from industry. Relevant governmental organizations have identified the immediate needs of earthquake victims in the three days following the disaster. The collected data is transformed into information/knowledge through data engineering and data analytics in the Digital World which is named "Activities" in the RAA Model. Transformed information/knowledge transmitted to EM stakeholders such as Suppliers, Logical Firms, Public, Governmental Organizations, Local Authorities in the real world. Figure 1 illustrates the RAA model approach which highlights the Actors, Resources, and Activities in earthquake emergency.

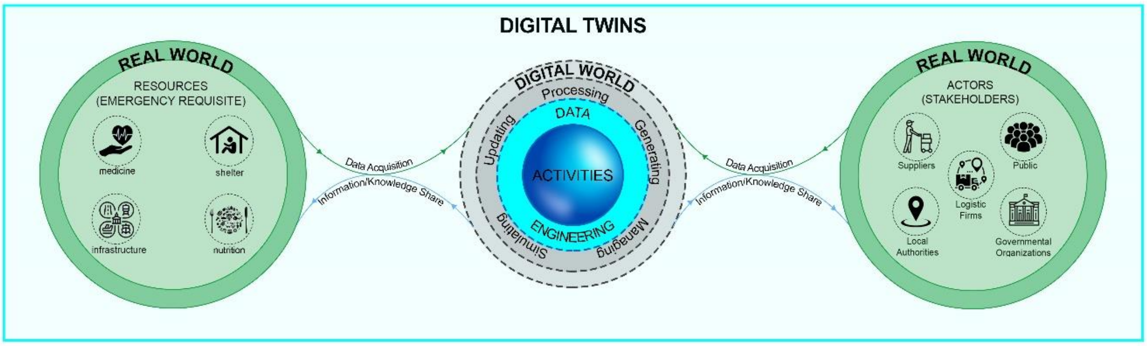

Figure 1: RAA model approach for the digital twins application in earthquake emergency management.

Discussion

The proposed framework offers a viable solution for addressing the challenges faced by individuals stranded during emergencies by providing fast and reliable methods of information acquisition. Using DT, it enables the rapid distribution of knowledge, enhancing situational awareness and facilitating efficient decision-making processes. The integration of KM capabilities with DT allows for real-time transparency and comprehensive monitoring of events during emergencies, empowering stakeholders to access valuable information for future instances. This fosters continuous improvement and increased resilience, while also enabling quick decision support and scenario analysis. By streamlining KM, emergency responders can collaborate effectively, reducing response time and mitigating negative consequences. Additionally, the framework enhances risk mitigation and sustainability efforts, enabling swift intervention in emergency situations like earthquakes.

Challenges, Opportunities, and Future Prospects

DT enables real-time monitoring and analysis of emergencies, enabling rapid decision-making and generating meaningful insights. Thus, appropriate intervention strategies can be determined quickly. Additionally, DT facilitates risk analysis by simulating emergency scenarios. Ensuring the integration of data from various sources triggers a more comprehensive emergency KM. Analyzing resources within the scope of the proposed DT framework can enable effective and efficient KM. However, for DT to create meaningful insight and make decisions, it must be fed with accurate and reliable data. Ensuring data security and privacy can be a challenge. In addition, big data are transferred to DT from different sources in emergency situations. Collecting, storing, processing, and analyzing data is another challenging task. It is important to harmonize big data from different sources and interpret it correctly. Despite all the challenges, the establishment of the proposed conceptual DT framework in light of the possible benefits can provide further analysis and prediction for emergencies. In the future, the predictive capabilities of DT may be improved by using more complex data analytics techniques and AI algorithms. By integrating IoT technologies into the system, real-time monitoring and intervention of emergencies can become more effective. In emergency situations, the selection of a distributed computing system for data management and processing becomes crucial. Given the need for swift action and rapid data transfer, leveraging fog or edge computing can serve as a viable solution for data storage. The proposed conceptual framework can create a common platform that can provide greater integration between different disciplines. For example, by combining and analyzing data from different fields such as meteorology, geology, sociology, and engineering, it may be possible to manage emergencies more comprehensively. Integration of immersive technologies can be a powerful tool for training emergency managers and responders. Furthermore, Smart City integration of proposed framework can indeed be a core solution to better prepare for and respond to earthquakes. Digital technologies and data-driven approaches can significantly enhance the resilience and safety of cities in earthquake-prone areas.

Conclusion

The proposed framework is operational and provides solutions for KM via DT for post-earthquake emergency. DT enables real-time monitoring, assisting stakeholders such as governmental organizations in gathering valuable knowledge for future emergencies, thus promoting continuous improvement and resilience. Transparent KM enhances coordination among emergency responders, leading to efficient actions. Furthermore, the framework contributes to risk mitigation and intervention speed in emergencies such as earthquakes. Future research could focus on integrating AI algorithms and data analytics techniques to address these limitations and enhance the proposed system. While the current focus of the proposed system is on addressing the needs of victims within the first three days following an earthquake, future research could explore additional needs of victims, such as hygiene or psychological support.

References

Ahn, E., & Kim, S. (2023). Digital twin application and bibliometric analysis for digitization and intelligence studies in geology and deep underground research areas. Data, 8(4), 73. https://doi.org/10.3390/data8040073

Boshara, M. A. E., Woods, P. C., & Elshaiekh, N. E. M. (2020). *Knowledge Management Support to Public Health in Humanitarian Emergency*.

Dorasamy, M., Raman, M., & Kaliannan, M. (2013). Knowledge management systems in support of disasters management: A two decade review. *Technological Forecasting and Social Change*, 80(9), 1834-1853.

Egorov, I., Polzunova, N., & Polzunov, I. (2021). The digital twin is an artifact of modern production systems. *SHS Web of Conferences*, 93, 01017. https://doi.org/10.1051/shsconf/20219301017

Goode, N., Salmon, P., Spencer, C., McArdle, D., & Archer, F. (2016). Defining disaster resilience: comparisons from key stakeholders involved in emergency management in Victoria, Australia. *Disasters*, 41(1), 171-193. https://doi.org/10.1111/disa.12189

Grieves, M., & Vickers, J. (2016). Origins of the digital twin concept. *Florida Institute of Technology*, 8, 3-20.

Jha, R., Lang, W., & Jedermann, R. (2021). Finding Earthquake Victims by Voice Detection Techniques. *Engineering Proceedings*, 10(1), 69.

Othman, S., & Beydoun, G. (2016). A metamodel-based knowledge sharing system for disaster management. *Expert Systems With Applications*, 63, 49-65. https://doi.org/10.1016/j.eswa.2016.06.018

Otundo, J. (2023). Knowledge management for competitiveness and organizational performance. International *Journal of Research in Education Humanities and Commerce*, 04(01), 12-18. https://doi.org/10.37602/ijrehc.2023.4202

Pedraza-Martinez, A. J., Stapleton, O., & Van Wassenhove, L. N. (2013). On the use of evidence in humanitarian logistics research. *Disasters*, 37, S51-S67.

Shaharuddin, S., Maulud, K., Rahman, S., & Ani, A. (2022). Digital twin for indoor disaster in smart city: a systematic review. *The International Archives of the Photogrammetry Remote Sensing and Spatial Information Sciences*, *XLVI-4/W3-2021*, 315-322. https://doi.org/10.5194/isprs-archives-xlvi-4-w3-2021-315-2022

Židek, K., Pitel, J., Adamek, M., Lazorik, P., & Hošovský, A. (2020). Digital twin of experimental smart manufacturing assembly system for industry 4.0 concept. *Sustainability*, 12(9), 3658. https://doi.org/10.3390/su12093658

Gao, J., & Bernard, A. (2018). An overview of knowledge sharing in new product development. *The International Journal of Advanced Manufacturing Technology*, *94*, 1545-1550.

Ontology Research Fields in the Cultural Heritage Domain

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Abstract

Cultural Heritage (CH) refers to a vast collection of data from various professions, which is constantly updated and processed on separate platforms by experts in different fields. This complexity results in intricate knowledge structures. Achieving a universally understandable representation of CH knowledge requires the collaboration of an interdisciplinary team and the management of interoperable complex knowledge. Development of a CH ontology provides a foundation for robust Knowledge Management (KM), facilitating an interoperable platform for sustainable knowledge transfer. This study aims to identify the main research clusters of ontology research within CH literature. Scientometric analysis of bibliometric data, visualized through mapping, reveals a recent emphasis on the interoperability of ontology studies in CH and Semantic Web technologies integration. The limitations of the research are that the bibliometric search consists only of journal articles and only in English. Future research is expected to focus on the seamless integration of CH domain ontologies, Semantic Web, and Artificial Intelligence (AI) technologies to provide a comprehensive Semantic KM.

Keywords: *cultural heritage (CH), ontology, knowledge management (KM), semantic web, artificial intelligence (AI)*

Introduction

Cultural Heritage (CH) refers to the tangible and intangible cultural elements of national identity that reflect past social and cultural human activities. It encompasses a wide range of human activities including eating, dressing, celebrating, and belief systems within civilizations (Kalita & Deka, 2020). Due to the interdisciplinary nature and historical significance, CH is a knowledge-based discipline, which requires a multidisciplinary approach. Predictions, interpretations and conclusions regarding CH can be made by comparing available data with existing information. Collaboration between researchers from different fields, using their own methods, computational models, or vocabularies, can lead to a diverse flow of knowledge (Hellmund et al., 2018). Ontologies enable information to be organized and reused. In the context of the semantic web, ontologies enable machines to understand information and query data efficiently (Doerr, 2009). Designing an ontological model in the context of CH triggers an interdisciplinary observation and semantic representation of CH elements (Messaoudi et al., 2018).

Ontology provides a shared Knowledge Management (KM) platform for researchers who need to exchange knowledge in a specific field of expertise. It comprises machine-interpretable definitions of domain-related concepts and their interrelationships (Noy and McGuinness 2001). Ontology creates a semantic network of linked information. The purpose of ontology development is to establish a common semantic information platform for both humans and machines (Cursi et al. 2022). Ontology can preserve the relationships and meanings between data. An ontology developed for any field can be used multiple times because it covers the content and mechanism of the related field. Possible shortcomings can be resolved by extending the domain ontology, reducing reimplementation costs in a KM system. When domain knowledge is represented through a common and shared language, it becomes understandable to humans, automated computer systems, and web agents. Web services and search engines use semantically enriched information to provide intelligent and context-aware applications, resulting in improved performance in terms of fast and accurate information retrieval (Ranjgar et al. 2022).

This study aims to answer a key question:

RQ1. How can Ontology enhance Knowledge Management in CH?

To answer this question, below-listed sub-questions are responded in this study.

SRQ1. What are the challenges and tendencies in ontology research in the CH domain?
SRQ2. What are the research areas related to ontology research in the CH domain?
SRQ3. What are the gaps in ontology research in the CH domain?
SRQ4. What are the trends in ontology research in the CH domain?
SRQ5. What are the future prospects for ontology research in the CH domain?

The main purpose of this article is to classify the mainstream research areas of Ontology research in the CH domain. The aim is to capture gaps and current research trends and make predictions for future research areas in this field.

The following section provides research methodology for the paper, scientometric analysis results, by discussing all the challenges, gaps and trends of Ontology research in CH domain. Finally, the conclusion synthesizes the principal findings derived from the investigation of ontology research within the CH domain, along with the emerging trends identified in the scholarly literature.

Methodology

A three-stage workflow was adopted to examine the status of Ontology research in the CH domain. Bibliometric search, scientometric mapping, and scientometric analysis constitute these three stages. The literature review for the use of Ontology research in the CH domain covers articles published from 2002 to June 2023. Collecting data from various databases can provide more comprehensive results than taking a single piece of data. However, including the same articles in databases causes crowding. Data analysis tools for scientometric analysis have shortcomings in combining data. This limitation prevents merging data from various databases. Therefore, a single database was used for data collection. Bibliometric search was performed on Scopus database because of wider coverage than other databases in the first stage of workflow (Aghaei Chadegani et al., 2013). Data collected through bibliometric search creates a snapshot of the literature. Their research for that period alone results in examining gaps and trends. Providing a dynamic knowledge graph can reflect research more efficiently. However this is a limitation for the research. Scopus employs Boolean syntax and an API search system to refine the search. Language limitation and filtering only journal articles are other limitations of the research. The second stage, Scientometric mapping, analyzes bibliometric data and reveals the relationships between disciplines, fields, and articles (Cobo et al., 2011). VOSviewer application was used to map and analyze bibliometric data collected from the Scopus database. VOSviewer can visualize large networks with using natural language processing and text-mining techniques (van Eck & Waltman, 2014). In this article, keyword combinations were clustered and sorted to examine Ontology research in the CH domain.

Scientometric Analysis and Results

Bibliometric Search:

Booelean search was used to sift through the results and find articles that were highly linked to the combined research keywords. Limitations were applied to the bibliometric search to achieve clearer results. The bibliometric search entry is shown in Figure 1 with the applied limitations. This research yielded 698 articles. By applying restrictions such as language, document type, document source, subject area, and keywords, 177 articles that were highly related to the research topic were obtained.

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TITLE-ABS-KEY ( {ontology} AND {cultural heritage} OR {built-heritage} OR {ancient city} OR {ancient site} ) AND ( LIMIT-TO ( SRCTYPE , "j" ) ) AND ( LIMIT-TO ( SUBJAREA , "COMP" ) OR LIMIT-TO ( SUBJAREA , "SOCI" ) OR LIMIT-TO ( SUBJAREA , "ARTS" ) OR LIMIT-TO ( SUBJAREA , "ENGI" ) OR LIMIT-TO ( SUBJAREA , "DECI" ) ) AND ( LIMIT-TO ( DOCTYPE , "ar" ) ) AND ( LIMIT-TO ( LANGUAGE , "English" ) ) AND ( LIMIT-TO ( EXACTKEYWORD , "Ontology" ) OR LIMIT-TO ( EXACTKEYWORD , "Semantics" ) OR LIMIT-TO ( EXACTKEYWORD , "Semantic Web" ) OR LIMIT-TO ( EXACTKEYWORD , "Ontologies" ) OR LIMIT-TO ( EXACTKEYWORD , "CIDOC CRM" ) OR LIMIT-TO ( EXACTKEYWORD , "Metadata" ) OR LIMIT-TO ( EXACTKEYWORD , "Ontology&apos;s" ) OR LIMIT-TO ( EXACTKEYWORD , "Linked Data" ) OR LIMIT-TO ( EXACTKEYWORD , "Knowledge Based Systems" ) OR LIMIT-TO ( EXACTKEYWORD , "Knowledge Management" ) OR LIMIT-TO ( EXACTKEYWORD , "Interoperability" ) OR LIMIT-TO ( EXACTKEYWORD , "Data Handling" ) OR LIMIT-TO ( EXACTKEYWORD , "Information Retrieval" ) OR LIMIT-TO ( EXACTKEYWORD , "Knowledge Representation" ) OR LIMIT-TO ( EXACTKEYWORD , "CIDOC-CRM" ) OR LIMIT-TO ( EXACTKEYWORD , "Knowledge Base" ) OR LIMIT-TO ( EXACTKEYWORD , "Linked Open Data" ) OR LIMIT-TO ( EXACTKEYWORD , "Open Data" ) OR LIMIT-TO ( EXACTKEYWORD , "Linked Open Datum" ) OR LIMIT-TO ( EXACTKEYWORD , "Ontology Evaluation" ) OR LIMIT-TO ( EXACTKEYWORD , "Virtual Reality" ) OR LIMIT-TO ( EXACTKEYWORD , "Data Integration" ) OR LIMIT-TO ( EXACTKEYWORD , "Digital Storage" ) OR LIMIT-TO ( EXACTKEYWORD , "Knowledge Acquisition" ) OR LIMIT-TO ( EXACTKEYWORD , "Semantic Enrichment" ) OR LIMIT-TO ( EXACTKEYWORD , "Semantic Web Technology" ) OR LIMIT-TO ( EXACTKEYWORD , "Semantic-Web" ) OR LIMIT-TO ( EXACTKEYWORD , "User Experience" ) OR LIMIT-TO ( EXACTKEYWORD , "Visualization" ) OR LIMIT-TO ( EXACTKEYWORD , "Artificial Intelligence" ) OR LIMIT-TO ( EXACTKEYWORD , "Augmented Reality" ) OR LIMIT-TO ( EXACTKEYWORD , "Data Structures" ) OR LIMIT-TO ( EXACTKEYWORD , "HBIM" ) OR LIMIT-TO ( EXACTKEYWORD , "Mapping" ) OR LIMIT-TO ( EXACTKEYWORD , "Natural Language Processing" ) OR LIMIT-TO ( EXACTKEYWORD , "Ontology Development" ) OR LIMIT-TO ( EXACTKEYWORD , "User Interfaces" ) OR LIMIT-TO ( EXACTKEYWORD , "Computational Ontology" ) OR LIMIT-TO ( EXACTKEYWORD , "Data Mining" ) OR LIMIT-TO ( EXACTKEYWORD , "Deep Learning" ) OR LIMIT-TO ( EXACTKEYWORD , "Information System" ) OR LIMIT-TO ( EXACTKEYWORD , "Internet Of Things" ) OR LIMIT-TO ( EXACTKEYWORD , "Knowledge Graph" ) OR LIMIT-TO ( EXACTKEYWORD , "Learning Systems" ) OR LIMIT-TO ( EXACTKEYWORD , "Linked Datum" ) OR LIMIT-TO ( EXACTKEYWORD , "Linked Open Data (LOD)" ) OR LIMIT-TO ( EXACTKEYWORD , "Maps" ) OR LIMIT-TO ( EXACTKEYWORD , "Metadata Interoperability" ) OR LIMIT-TO ( EXACTKEYWORD , "Natural Language Processing Systems" ) OR LIMIT-TO ( EXACTKEYWORD , "Ontological Analysis" ) OR LIMIT-TO ( EXACTKEYWORD , "Ontology Design Patterns" ) OR LIMIT-TO ( EXACTKEYWORD , "Ontology Engineering" ) OR LIMIT-TO ( EXACTKEYWORD , "Ontology Matching" ) OR LIMIT-TO ( EXACTKEYWORD , "Open Datum" ) OR LIMIT-TO ( EXACTKEYWORD , "RDF" ...
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Figure 1: Summary of bibliometric search input.

Scientometric Analysis and Mapping:

Keywords identifies important points in research (Su & Lee, 2010; He et al., 2017). The research utilised Vosviewer to apply natural language processing and text mining methods, creating a network visualisation map to display the relationship between keywords and cluster main research areas (Eck & Waltman, 2014). The use of index keywords, rather than solely relying on the authors' chosen keywords, prevented any overlooked keywords. Figure 2 displays the network visualization map of the keywords co-occurrence analysis results. A summary of the keyword list is provided in Table 1.

The linked keywords were clustered using VOSviewer, allowing for the interpretation of main clusters in Ontology research in the CH domain. In the keyword network shown in Figure 2, each color represents a separate subdomain. The clusters are named as Ontology Lifecycle (red coded), Semantic Knowledge Management (green coded), AI-based Knowledge Generation (blue coded), Semantic Search (yellow coded), Semantic Web Technologies for the IoT (purple coded), and Semantic Interoperable Information Management (turquoise coded).

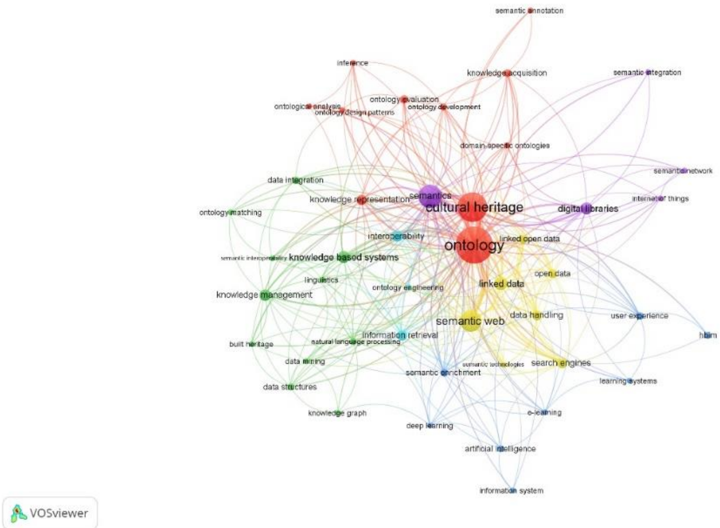

Figure 2: Map of keyword co-occurrence analysis of Ontology research in the CH domain (from 2002 to June 2023).

Table 1. Results of keyword co-occurrence analysis for Ontology research in the CH domain from 2002 to June 2023.

	Link	Total Link Strength	Occurrence Frequency	Average Citation	Average Normalized Citation	Average Publication Year
Cluster 1: Ontology Lifecycle (red-coded)						
Cultural heritage	40	183	73	11,81	0,90	2017,77
Domain specific ontologies	9	13	3	12,33	0,43	2016,67
Knowledge representation	15	36	9	8,56	0,79	2017,44
Ontological analysis	6	10	3	8,33	2,60	2019,67
Ontology	42	279	116	13,97	0,97	2017,46
Ontology design pattern	7	8	3	12,00	1,99	2018,00
Ontology development	13	18	4	9,00	0,37	2012,00
Ontology evaluation	10	14	6	4,50	1,33	2021,33
Cluster 2: Semantic Knowledge Management (green-coded)						
Built heritage	8	13	3	30,67	2,95	2020,00
Data structures	12	15	4	123,25	1,46	2015,25
Knowledge based systems	22	52	13	16,00	1,37	2016,77

Knowledge graph	5	6	3	21,33	1,62	2020,00
Knowledge management	15	30	11	14,00	1,29	2015,09
Natural language processing	14	17	4	23,50	1,38	2016,00
Semantic interoperability	11	14	3	16,67	0,85	2015,00
Cluster 3: AI-Based Knowledge Generation (blue-coded)						
Artificial intelligence	9	9	4	3,75	0,62	2014,25
HBIM	3	5	4	5,00	1,20	2021,50
Information systems	4	5	3	4,33	0,39	2017,33
Learning systems	5	7	3	12,33	0,91	2014,00
Semantic enrichment	18	26	5	18,80	1,83	2015,40
User experience	12	20	5	29,20	1,60	2018,80
Cluster 4: Semantic Search (yellow-coded)						
Linked data	23	65	15	6,07	0,66	2018,67
Linked open data	18	36	7	14,86	1,42	2018,14
Open data	16	34	7	9,43	0,83	2019,86
Search engines	16	39	9	19,78	1,04	2013,22
Semantic web	26	104	38	16,79	1,25	2018,45
Cluster 5: Semantic Web Technologies for the IoT (purple-coded)						
Digital libraries	17	42	13	9,38	0,94	2015,46
Internet of things	8	10	3	7,67	1,02	2019,00
Semantic integration	4	7	3	3,33	0,23	2020,00
Semantic network	5	6	3	9,33	0,68	2017,33
Semantics	37	144	46	25,87	0,94	2016,33
Cluster 6: Semantic Interoperable Information Management (turquoise-coded)						
Information retrieval	17	9	9	22,00	1,10	2011,56
Interoperability	17	10	10	66,00	1,85	2014,40
Ontology engineering	4	3	3	24,33	1,99	2014,67

The red coded cluster called "Ontology Lifecycle" and is associated with CH Ontology processes. CH Ontology serves is a model for representing knowledge by capturing concepts, relationships, and properties related to CH. The Ontology Design Pattern is proposed to increase the usability and understandability of the CH Ontology. An ontology can be developed manually from scratch or by integrating existing ontologies. Integration involves using existing ontologies to develop a new ontology. Integration involves using existing ontologies to develop a new ontology. Ontological Analysis is the method used to integrate existing ontologies into the CH Ontology. The increasing number of studies in this area has the potential to benefit CHKM. The development of these methods may serve as the foundation for AI-based CHKM in the future.

The green coded cluster called "Semantic Knowledge Management" and is associated with the integration of CH Ontology with semantic web technologies. Semantic Web Technologies help to enhance the accessibility of CH knowledge by aiding in its preservation, digitalization, and sharing. Semantic KM can provide numerous benefits for CH Ontology, including decision-making support, semantic enrichment, data sharing, and interoperability.

The blue coded cluster called "AI-based Knowledge Generation" can be attributed to the benefits of AI technologies to the CH Ontology. These technologies can enhance knowledge representation through semantic enrichment, automatic knowledge acquisition, intelligent data integration, recommendation systems, data management, and knowledge representation. AI and semantic web technologies can increase the accessibility of CH Ontology, contributing to the creation of educational platforms.

The yellow coded cluster called "Semantic Search" is associated with the integration of CH Ontology into search engines in order to increase the accessibility of CH information. Semantic search systems use ontologies to provide descriptions of CH concepts and relationships, triggering semantic inference and interpretation from CH information.

The purple coded cluster called "Semantic Web Technologies for the IoT" and is linked to the use of the Internet of Things for creating interactive platforms for cultural heritage information. The IoT has the potential to ensure the sustainability and dissemination of CH knowledge, while also providing enriched user experiences through the development of interactive CHKM models.

Turquoise-coded cluster called "Semantic Interoperable Information Management" is associated with a more accessible, interconnected, and meaningful representation of information. Intelligent and user-friendly CHKM systems can be developed by managing and interconnecting CH information through semantic networks.

Discussions

The integration of emerging technologies into CH researches have primarily focused on physical conservation. However, this approach has caused difficulties in ensuring comprehensive conservation of CH information. The result was the conceptualization and development of the CH Ontology for CHKM. Despite the recognized importance of CH Ontology, existing literature shows that research in this area is relatively scarce. Developing the CH Ontology presents fundamental challenges in various ontology-related tasks, including design, configuration, and evaluation. These challenges increase the complexity of CH Ontology research and highlight the complexity of the ontology development process. The interdisciplinary nature of CH data poses an additional obstacle for research on CH ontology. The flexible semantics required for CH Ontology must accommodate various data types (Cacciotti, 2015; Belhi et al., 2019). These various data types can be easily integrated into CH KG by using the semantic enrichment process applied to CH Ontology.

The literature on CH Ontology shows that there has been a noticeable increase in the use of Semantic Web and AI technologies (Ozturk & Ozen, 2020). These areas of research are prominent and dynamic, particularly in the context of CHKM development. The development of the CH Ontology has been instrumental has played a crucial role in ensuring semantic interoperability and effective representation of CH knowledge. The integration of Semantic Web Technologies into the CH Ontology framework has the potential to promote interdisciplinary interoperability in different fields. Furthermore, the strategic convergence of Semantic Web Technologies and AI pave the way for new digital platforms in the CH sector. The integration of these technologies can lead to the emergence of user-centered knowledge sharing platforms, where CH Ontology serves as a core infrastructure for chatbot-based services. The convergence of technologies, including IoT, can serve as a catalyst for the development of Cultural Heritage (CH) Digital Twins, which can improve the accessibility of CH information and enhance the user experience. This synergy can also lead in new dimensions of interaction and understanding in the field of CH.

Conclusion

This study aims to reveal the scientific trends of Ontology research in the CH literature. For this purpose, bibliometric research and scientometric analysis were conducted. As a result of the research, it was revealed that the CH Ontology can increase the accessibility and maintainability of CH information by triggering the semantic CHKM. In addition, the integration of AI technologies enhances the reach of the CH Ontology and expands its scope. The expected outcomes of this integration include facilitating innovative knowledge sharing platforms in the future. Therefore, prospective research should focus on seamlessly integrating CH domain ontologies, Semantic Web Technologies, and AI technologies to provide comprehensive Semantic KM. However, it is imperative to acknowledge a limitation of this study, which relates to bibliometric screening and primarily covers journal articles with English language restrictions. The data set used in scientometric mapping and analysis was derived from academic research, excluding practical and commercial innovations. Future research could benefit from incorporating data from practitioners and commercial organizations to further enrich the analysis and thus draw more comprehensive and informed conclusions.

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References

Aghaei Chadegani, A., Salehi, H., Yunus, M., Melor, M., Farhadi, H., Fooladi, M., Farhadi, M., & Ale Ebrahim, N. (2013). A comparison between two main academic literature collections: Web of science and scopus databases. *Asian Social Science*, 9(5), 18–26. https://doi.org/10.5539/ass.v9n5p18

Belhi, A., Abu-Musa, T., Al-Ali, A. K., Bouras, A., Foufou, S., Yu, X., Zhang, H. (2019). Digital heritage enrichment through artificial intelligence and semantic web technologies. In *Proceedings - 2019 4th International Conference on Communication and Information Systems, ICCIS 2019* (pp. 180–185). https://doi.org/10.1109/ICCIS49662.2019.00039

Cacciotti, R. (2015). Integrated knowledge-based tools for documenting and monitoring damages to built heritage. *The International Archives of the Photogrammetry Remote Sensing and Spatial Information Sciences*, XL-5/W7, 57-63. https://doi.org/10.5194/isprsarchives-xl-5-w7-57-2015.

Cobo, M. J., López-Herrera, A. G., Herrera-Viedma, E., & Herrera, F. (2011). An approach for detecting, quantifying, and visualizing the evolution of a research field: A practical application to the Fuzzy Sets Theory field. *Journal of Informetrics*, 5(1), 146–166. https://doi.org/10.1016/j.joi.2010.10.002.

Cursi, S., Martinelli, L., Paraciani, N., Calcerano, F., & Gigliarelli, E. (2022). Linking external knowledge to heritage BIM. *Automation in Construction*, 141(October 2021). https://doi.org/10.1016/j.autcon.2022.104444

Doerr, M. (2009). Ontologies for cultural heritage. In *Handbook on ontologies* (pp. 463-486). Berlin, Heidelberg: Springer Berlin Heidelberg. ISBN: 3540926739, 9783540926733

Eck, N. J., & Waltman, L. (2014). Visualizing Bibliometric Networks. In Ding, Y. (Ed.), Rousseau, R. (Ed.), Wolfram, D. (Ed.), *Measuring Scholarly Impact: Methods and Practice* (pp. 285-321). https://doi.org/10.1007/978-3-319-10377-8_13.

He, Q., Wang, G., Luo, L., Shi, Q., Xie, J., & Meng, X. (2017). Mapping the managerial areas of Building Information Modeling (BIM) using scientometric analysis. *International Journal of Project Management*, 35(4), 670–685. https://doi.org/10.1016/j.ijproman.2016.08.001

Hellmund, T., Hertweck, P., Hilbring, D., Mossgraber, J., Alexandrakis, G., Pouli, P., Siatou, A., & Padeletti, G. (2018). Introducing the heracles ontology—semantics for cultural heritage management. *Heritage*, 1(2), 377–391. https://doi.org/10.3390/heritage1020026

Kalita, D., & Deka, D. (2020). Ontology for preserving the knowledge base of traditional dances (OTD). *Electronic Library*, 38(4), 785–803. https://doi.org/10.1108/EL-11-2019-0258

Messaoudi, T., Véron, P., Halin, G., & De Luca, L. (2018). An ontological model for the reality-based 3D annotation of heritage building conservation state. *Journal of Cultural Heritage*, 29, 100–112. https://doi.org/10.1016/j.culher.2017.05.017

Noy, N. F., & McGuinness, D. L. (2001). Ontology Development 101: A Guide to Creating Your First Ontology. Stanford Knowledge Systems Laboratory, March, 25. https://doi.org/10.1016/j.artmed.2004.01.014

Ozturk, G. B., & Ozen, B. (2020). Technology Use in Archeology and Historical Building Research: A Citation, Bibliographic Coupling, and Document Analysis. *Journal of Construction Engineering, & Management Innovation, 3*, 141-157.

Ranjgar, B., Sadeghi-Niaraki, A., Shakeri, M., & Choi, S. (2022). An ontological data model for points of interest (poi) in a cultural heritage site. *Heritage Science*, 10(1). https://doi.org/10.1186/s40494-021-00635-9

Su, H. N., & Lee, P. C. (2010). Mapping knowledge structure by keyword co-occurrence: A first look at journal papers in Technology Foresight. *Scientometrics*, 85(1), 65–79. https://doi.org/10.1007/s11192-010-0259-8

Maturity of Digital Twins from an Artificial Intelligence Perspective

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Abstract

Due to its potential to elevate buildings as a system to a level where they turn into cognitive (self-reliant autonomous decision-making and acting) entities, the adoption of Digital Twins (DT) has been significantly increased. Therefore, maturity models have become essential for evaluating and enhancing the advancement in DT to assess the adoption of technology across various industries. The paper proposes a maturity model approach from an Artificial Intelligence (AI) perspective to gain insights into the adoption and implementation of DT in the AEC-FM industry, which distinguishes it from the existing maturity models. Additionally, making a comparison between the interpretation of the term 'cognition' in computer science and its understanding within the AEC-FM industry, presenting pre-classified levels of cognition in literature. In this regard, a literature review is conducted to figure-out the gaps in previous DT maturity model studies. The proposed perspective could cover the missing AI perspective in designing maturity models and provide insights into leveraging the semantics of the term 'cognitive' in the AEC-FM industry. Future research directions could further explore various dimensions of DT maturity models and cognition levels within the AEC-FM industry, considering practical challenges and potential applications of DT implementations in-depth.

Keywords: *artificial intelligence, digital twins, maturity model, the AEC-FM industry*

Introduction

As Digital Twins (DT) becomes increasingly prevalent across various industries including manufacturing, construction, aerospace, healthcare, and agriculture since it is first introduced by Michael Grieves in 2003 (Grieves, 2014), there is a growing need for tools to evaluate its current state and offer insights for enhancement. While there is no commonly agreed definition of DT, in most of the definitions it consists of three main elements: the virtual side, the physical side and the data/information flow (feedback and feed-forward loops) between the physical and virtual to connect them. Maturity models are essential for evaluating the present uptake and offering a structured framework for its ongoing advancement and integration of DT. There are different approaches exist in literature to derive DT development and by this way the maturity. Grieves, introduced the concepts *Digital Twin Prototype*, *Digital Twin Instance*, *Digital Twin Aggregate, and Digital Twin Environment* by further expanding the understanding of DT aspects (Grieves & Vickers, 2017). Kritzenger et al. focused on level of data integrated between physical and virtual environments and defined three different levels which are *Digital Model, Digital Shadow, and Digital Twin* (Kritzenger et al., 2018). On the other hand, Kart et al. outlined four level of DT based on their capabilities: *Descriptive Twin, Diagnostic Twin, Predictive Twin, and Prescriptive Twin* (Kart et al., 2013).

Numerous maturity models exist in DT literature. However, they defined the maturity levels and dimensions related to capabilities and features of a DT. The aim of this research is to suggest a distinct perspective on assessing maturity by focusing specifically on the AI perspective. Since the ultimate point researchers and industry practitioners aim to reach is developing an intelligent system, DT, capable of *self-reliant autonomous decision-making* or in other word *'can think and/or act like human does'* the way inevitably navigate researchers to focus on terms 'AI' and 'cognition/consciousness'.

Building upon the above premises, this paper aims to investigate following research questions:

RQ1: Classification of the existing DT maturity models?
RQ2: What are strengths and weaknesses of the existing DT maturity models?
RQ3: What should be assessed for a Cognitive DT?
RQ4: The distinction between the determination of Cognition/Consciousness in computer science and the AEC-FM field?
RQ5: How does the proposed AI-based perspective for DT maturity differ from the previously used maturity perspectives?

In the following sections, the paper discusses various DT maturity models and emphasizes the central concepts that form the basis of the proposed maturity perspective.

Existing Maturity Models in DT Literature

Maturity models developed for DT have been devised to evaluate and enhance the adoption of DT across diverse industries. There are eight existing maturity model developed for DT in literature which are from aerospace (Medina et al, 2022), manufacturing (Madni et al., 2019; Hu et al.,2023; Mo et al., 2023), asset management (Chen et al., 2021), construction (Boje et al.,2020; Evans et al., 2019) and smart city (Shemyakina et al., 2022). Figure 1 illustrates the existing maturity models in DT literature.

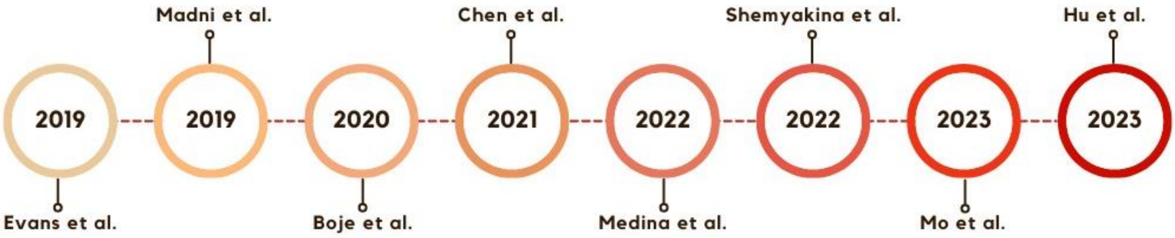

Figure 1: Existing maturity models.

In the highest level of all existing maturity models, the scenario that the system attains cognitive capabilities is advocated. For example, in the maturity model developed by Evans et al. (2019), six maturity levels were outlined, with the highest level featuring complete self-governance where the system can conduct autonomous operations and maintenance. At this stage, the system can learn the preferences of humans (generating patterns) and takes minimal action or without human interaction. Mo et al. (2023) identified five levels of autonomy and assessed maturity across various categories, characteristics, and functionalities, for instance a system achieving the highest level of autonomy in 'data integration' can perform self-optimization activities. Similarly, in the model presented by Chen et al. (2021), the system transitions to semi-automatic or fully automatic functioning and is capable of providing decision support independently. Likewise, Madni et al. (2019) asserted that in the highest level of maturity within their developed model, the system demonstrates a high degree of autonomy and possesses supervised, unsupervised, and reinforcement learning capabilities. Although the existing maturity models delve into DT literature and present maturity models based on the definition, features, and functionalities, they fall short in defining the ultimate point a DT can reach according to cognitive capabilities it might have.

Artificial Intelligence (AI) Approaches

Artificial Intelligence (AI) is a field with the potential to transform industries. Since the concept first introduced by John McCarthy (McCarthy et al., 1955), numerous other definitions have emerged, each emphasizing different facets of AI. The ultimate goal of DT, regardless of the industry, is to define a system where the feedback and feed-forward loops between the real world and its virtual representation are completed, thus establishing an endless cycle of development for the data-information-knowledge (DIK) transformation cycle. AI is the primary technology being used in DT, as it offers sophisticated data processing techniques to extract insights from the captured data (Ozturk, 2021). For this reason, the development of a maturity model for DT with cognitive capabilities, the assessment should be centred around AI perspective.

The proposed maturity approach aims not only to create intelligent systems but also to acquire insights into them. In this regard, the categorization of Stuart Russell and Peter Norvig is adopted in this research (Russell et al., 2010). According to their categorization, there are four AI approaches defined:

(a) Systems that think like human
"The automation of activities that we associate with human thinking, activities such as decision-making, problem solving, learning ..." (Bellman, 1978)

(b) Systems that think rationally
"The study of the computations that make it possible to perceive, reason, and act" (Winston, 1992)

(c) Systems that act like human
"The art of creating machines that perform functions that require intelligence when performed by people" (Kurzweil, 1990)

(d) Systems that act rationally
"Computational Intelligence is the study of the design of intelligent agents." (Poole et al., 1998)"

Since the time Alan Turing came with the idea of 'thinking machine' (Turing, 1950), the focus of AI studies shifted to find ways to create human-like systems. This question triggered another question; 'can machines ever reach to human cognition level?' by time and separated researchers into groups with different perspectives. While some of the researchers thinks that it will never be possible for a machine (French, 2012; Searle, 2014), some were seeing this as a certain outcome of technological advancements (Bostrom, 2015).

It is essential to understand the distinctions in thinking processes and behaviours to figure out AI approaches. Systems that emulate human thought processes, characterized by intuitive and experiential thinking styles, exemplify the approach of systems that think like human (Hongdizi et al., 2023). An illustration of this approach is seen in Building Occupancy Systems, which can predict future occupancy pattern by analysing the behaviours of human such as working hours and schedules, is a good example for this approach. On the other hand, systems that think rationally rely on logic and deliberate thinking (Pacini & Epstein, 1999). Building Information Modeling (BIM) Systems can be an example to this approach since the aim of these systems are optimization of building lifecycle by analysing several factors such as material cost and energy efficiency. Systems act like human tries to emulate human behaviours and responses. Smart Home Systems can learn and adapt the preferences of humans by time such as turning off lights when there is nobody in room. Lastly, systems that act rationally make decisions and turn them into action based on logic or predefined rules/principles. Intelligent Transportation Systems (ITS) uses rational decision-making strategies to control flow of the traffic or providing real-time data to travellers.

Cognition/Consciousness

Cognition is defined as, the mental processes involved in acquiring, storing, retrieving, and using information from the environment (Mitchell et al., 2002). In computer science literature, cognition has been classified into various levels. This paper adopts David Armstrong's categorization as its framework to reveal what are the required cognition capabilities to create a DT which demonstrates human cognition. Armstrong examined cognition across three distinct levels which are *Minimal Consciousness, Perceptual Consciousness, and Introspective Consciousness*.

According to this classification, the cognition level of a person sleeping is an example to Minimal Consciousness level. During sleep, humans are unable to perceive even though their sensory organs may be functioning. Regarding Perceptual Consciousness level, objects whose existence has been established in preceding levels are contextualized based on their relationships with other objects. At the Introspective Consciousness Level, the organism not only understands the external world (context) but also comprehends its internal world.

In last years, there is a new effort of combining DT with some semantic technologies process data in a way that human does. DT, as a platform, technology, and service, have potential to facilitate the development of cognitive systems. The term 'Cognitive Digital Twins' firstly introduced during an industry symposium. According to Zheng et al., in the coming years, Cognitive Digital Twin will emerge as the outcome of augmenting traditional Digital Twins with cognitive capabilities and incorporating diverse semantic technologies, such as Knowledge Graphs (KGs) and Natural Language Processing (NLP) (Zheng et al., 2022) (Table 1).

Table 1. Definitions of the term 'Cognitive Digital Twins' in the AEC-FM industry.

Reference	*Cognitive Digital Twins Definition*
Saracevic, (2017)	*'a virtual representation of a physical object or system across its lifecycle using real time data from IoT sensors and other sources to enable learning, reasoning and automatically adjusting for improved decision-making'*
Fernández et al., (2019)	*'a digital expert or copilot, which can learn and evolve, and that integrates different sources of information for the considered purpose'*
Lu et al., (2020)	*'DT with augmented semantic capabilities for identifying the dynamics of virtual model evolution, promoting the understanding of interrelationships between virtual models, and enhancing decision-making'*
Abburu et al., (2020b)	*'an extension of Hybrid Twin (HT) that incorporates cognitive features enabling the system to sense complex and unpredictable behaviour, reason about dynamic strategies for process optimization, and continuously evolve its digital structure and behaviour'*
Johansen et al., 2023	*'an extended version of traditional DT by integrating machine learning techniques to create hybrid, self-learning, and proactive systems, as well as leveraging the interaction between models and humans to support decision-making processes'*

In the AEC-FM industry, cognition is associated with the terms such as 'autonomous decision-making', 'perception', 'prescription', 'learning', and 'integration of different information sources', 'advanced technological capabilities'. However, according to meaning of the concept in computer science, cognition is perceived as more intricate than this. Moreover, the level of introspective consciousness remains a topic of debate even among researchers in computer science, and its understanding and application in the AEC-FM industry have yet to be clearly defined.

In contrast to the perspective found in previously developed maturity models, this approach aims to develop a Knowledge Management (KM) perspective focused on the collection, processing, generation of information, storage, distribution, and reuse of data. While the existing maturity models is beneficial in illuminating the current state of DT research and extent of technological capabilities employed, they lack an understanding of the term 'cognition' and human cognitive capabilities. In addition to the concerns addressed in literature such as 'autonomous decision-making', 'prediction', 'prescription', and 'model update frequency', the questions related to whether the system is aware of its context or if it can make inferences about its own functioning (introspection) should also be considered. In addition to diverging from the perspectives found in existing literature, the AI-based maturity perspective proposes a comprehensive, structural, and more development-oriented solution for the DT maturity subject.

Discussion

The primary aim behind the development of DT maturity models is to facilitate the adoption and implementation of DT and creating more intelligent, cognitive systems with minimal or no human interaction. AI is the key enabler technology for this purpose. However, the understanding of AI and associated concepts such as cognition varies between the realms of computer science and AEC-FM industry. This paper reviewed existing maturity models for DT and assessed those put forth by prior researchers. Through this review, gaps and misconceptions in literature are identified.

This study introduces a new approach for developing DT with advanced cognitive capabilities (self-reliant autonomous systems). Although the perspective proposed is better understood within the computer science environment, and its adoption and implementation outside of this domain are still in the early stages, the proposed approach contributes to the current literature and holds potential for enhancing future maturity assessment studies.

Conclusion

The paper proposes a novel approach according to evaluation of maturity of DT after analysing the existing DT maturity models in literature. The proposed method combines elements from different terms and compares the comprehension of AI in both computer science and the AEC-FM industry. While there are challenges in implementing the proposed approach in real-world situations, it holds promise for elevating the built environment from being merely "smart" to more "intelligent". This approach could facilitate the creation of symbiotic systems that integrate the built environment with human interactions, enhancing connectivity and synergy between the two. Future studies might involve developing a maturity model customized for the AEC-FM industry, considering the proposed approach, and/or expanding upon the suggested perspective by incorporating different levels of cognitive classification found in existing literature. The main result of this study is to introduce a novel maturity approach for future studies on digital transformation maturity, aiming to address misconceptions and gaps in the current the AEC-FM industry-based research commenting on cognition and intelligence.

References

Abburu, S., Berre, A. J., Jacoby, M., Roman, D., Stojanovic, L., & Stojanovic, N. (2020, June). Cognitwin–hybrid and cognitive digital twins for the process industry. *In 2020 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC)* (pp. 1-8). IEEE. DOI: 10.1109/ICE/ITMC49519.2020.9198403

Bellman, R. (1978). An Introduction to Artificial Intelligence: Can Computers Think? Boyd & Fraser Publishing. ISBN 0878350667, 9780878350667.

Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y. (2020). Towards a semantic Construction Digital Twin: Directions for future research. *Automation in Construction*, 114, 103179. https://doi.org/10.1016/j.autcon.2020.103179

Bostrom N. (2015). Superintelligence: Paths, Dangers, Strategies. Oxford University Press. Volume 25, pages 285–289. ISBN: 978-0-19-967811-2

Chen, L., Xie, X., Lu, Q., Parlikad, A. K., Pitt, M., & Yang, J. (2021). Gemini principles-based digital twin maturity model for asset management. *Sustainability*, 13(15), 8224. https://doi.org/10.3390/su13158224

Evans, S., Savian, C., Burns, A., & Cooper, C. (2019). Digital twins for the built environment: An introduction to the opportunities, benefits, challenges and risks. *Built Environmental News*.

Fernández, F., Sánchez, Á., Vélez, J. F., & Moreno, A. B. (2019). Symbiotic autonomous systems with consciousness using digital twins. In From Bioinspired Systems and Biomedical Applications to Machine Learning: *8th International Work-Conference on the Interplay Between Natural and Artificial Computation, IWINAC 2019*, Almería, Spain, June 3–7, 2019, Proceedings, Part II 8 (pp. 23-32). Springer International Publishing. DOI:10.1007/978-3-030-19651-6_3

French, R. M. (2012). Moving beyond the Turing test. *Communications of the ACM*, 55(12), 74-77. DOI:10.1145/2380656.2380674

Grieves, M. (2014). Digital twin: manufacturing excellence through virtual factory replication. *White paper*, 1(2014), 1-7.

Grieves M, and Vickers J (2017) Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems. Springer, 85-113. DOI:10.1007/978-3-319-38756-7_4

Hongdizi, J., Cui, Y. X., Zhou, X., & Zhai, H. K. (2023). Influence of analytic processing on divergent and convergent thinking tasks: The role of rational and experiential thinking styles. *Journal of Intelligence*, 11(2), 23. https://doi.org/10.3390/jintelligence11020023

Hu, W., Fang, J., Zhang, T., Liu, Z., & Tan, J. (2023). A new quantitative digital twin maturity model for high-end equipment. *Journal of Manufacturing Systems*, 66, 248-259. https://doi.org/10.1016/j.jmsy.2022.12.012

Johansen, S. T., Unal, P., Albayrak, Ö., Ikonen, E., Linnestad, K. J., Jawahery, S., ... & Løvfall, B. T. (2023). Hybrid and cognitive digital twins for the process industry. *Open Engineering*, 13(1), 20220418. https://doi.org/10.1515/eng-2022-0418

Kart, L., Linden, A., & Schulte, W. R. (2013). Extend your portfolio of analytics capabilities. Gartner Group, Stamford, CT.

Kurzweil, R. (1990). The age of intelligent machines (Vol. 580). Cambridge: MIT press. ISBN: 9780262610797

Lu, J., Zheng, X., Gharaei, A., Kalaboukas, K., & Kiritsis, D. (2020). Cognitive twins for supporting decision-makings of internet of things systems. In Proceedings of 5th International Conference on the Industry 4.0 Model for Advanced Manufacturing: AMP 2020 (pp. 105-115). Springer International Publishing.

Madni, A., Madni, C., & Lucero, S. (2019). Leveraging digital twin technology in model-based systems engineering. *Systems*, 7(1), 7. https://doi.org/10.3390/systems7010007.

McCarthy, J., Minsky, M. L., Rochester, N., and Shannon, C. E. (1955). A Proposal for the Dartmouth summer research project on artificial intelligence. Tech. rep., Dartmouth College. DOI: https://doi.org/10.1609/aimag.v27i4.1904

Medina, F. G., Umpierrez, A. W., Martínez, V., & Fromm, H. (2021, March). A maturity model for digital twin implementations in the commercial aerospace oem industry. In *2021 10th* *international conference on industrial technology and management (ICITM)* (pp. 149-156). IEEE. DOI:10.1109/ICITM52822.2021.00034

Mitchell, R. K., Busenitz, L., Lant, T., McDougall, P. P., Morse, E. A., & Smith, J. B. (2002). Toward a theory of entrepreneurial cognition: Rethinking the people side of entrepreneurship research. *Entrepreneurship Theory and Practice*, 27(2), 93-104. https://doi.org/10.1111/1540-8520.00001

Mo, F., Monetti, F. M., Torayev, A., Rehman, H. U., Mulet Alberola, J. A., Rea Minango, N., ... & Chaplin, J. C. (2023). A maturity model for the autonomy of manufacturing systems. The International *Journal of Advanced Manufacturing Technology*, 126(1), 405-428. https://doi.org/10.1007/s00170-023-10910-7

Ozturk, G. B. (2021). Digital twin research in the AECO-FM industry. *Journal of Building Engineering*, 40, 102730. https://doi.org/10.1016/j.jobe.2021.102730

Pacini, R., & Epstein, S. (1999). The relation of rational and experiential information processing styles to personality, basic beliefs, and the ratio-bias phenomenon. *Journal of Personality and Social Psychology*, 76(6), 972. https://doi.org/10.1037/0022-3514.76.6.972

Poole, D. I., Goebel, R. G., & Mackworth, A. K. (1998). Computational intelligence (Vol. 1). Oxford: Oxford University Press.

Russell S.J., Norvig, P., Davis E. (2010). Artificial intelligence: a modern approach. Prentice Hall, 2010. ISBN 0136042597, 9780136042594

Saracevic, F. (2017). Cognitive Digital Twin. I.B.M. Technical Report.

Searle, J.R (2014, October 9) "What Your Computer Can't Know". *New York Review of Books*, available at: www.nybooks.com/articles/archives/2014/oct/09/what-your-computer-cant-know/ (accessed May 10, 2024)

Shemyakina, T. Y., Gorelova, O. A., & Dyudyun, T. Y. (2022, January). Smart technologies for managing the urban environment: The use of "Digital Twins". *In Proceedings of the International Scientific Conference "Smart Nations: Global Trends In The Digital Economy"* Volume 2 (pp. 80-86). Cham: Springer International Publishing. DOI:10.1007/978-3-030-94870-2_11

Turing, A.M. (1950). "Computing machinery and intelligence," Mind, vol. 59, no. 236, pp. 433–460. https://doi.org/10.1093/mind/LIX.236.433

Winston, P. H. (1992). Artificial intelligence. Addison-Wesley Longman Publishing. ISBN 0201533774, 9780201533774

Zheng, X., Lu, J., & Kiritsis, D. (2022). The emergence of cognitive digital twin: vision, challenges and opportunities. *International Journal of Production Research*, 60(24), 7610-7632. https://doi.org/10.1080/00207543.2021.2014591

Demystifying the Potential of ChatGPT-4 Vision for Construction Progress Monitoring

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Abstract

The integration of Large Vision-Language Models (LVLMs) such as OpenAI's GPT-4 Vision into various sectors has marked a significant evolution in the field of artificial intelligence, particularly in the analysis and interpretation of visual data. This paper explores the practical application of GPT-4 Vision in the construction industry, focusing on its capabilities in monitoring and tracking the progress of construction projects. Utilizing high-resolution aerial imagery of construction sites, the study examines how GPT-4 Vision performs detailed scene analysis and tracks developmental changes over time. The findings demonstrate that while GPT-4 Vision is proficient in identifying construction stages, materials, and machinery, it faces challenges with precise object localization and segmentation. Despite these limitations, the potential for future advancements in this technology is considerable. This research not only highlights the current state and opportunities of using LVLMs in construction but also discusses future directions for enhancing the model's utility through domain-specific training and integration with other computer vision techniques and digital twins.

Keywords: *ChatGPT, construction, GPT-4 Vision, GPT-4V, large vision language model, large vision model, progress monitoring*

Introduction

The rapid advancement of Large Language Models (LLMs) has significantly shaped the field of natural language processing, placing these models at the center of text analysis and generation efforts. LLMs, known for their training on large datasets, have developed the remarkable capability to understand and produce text in a way that closely mimics human language. The widespread availability of platforms like ChatGPT (OpenAI, 2022) and Gemini (Google, 2023) has made these technologies accessible to more people, expanding their use across different fields. Alongside the advancements in language processing, the emergence of Large Vision-Language Models (LVLMs), also sometimes referred to as Large Vision Models, signifies a similar revolution within the realm of image processing and interpretation. These sophisticated artificial intelligence systems are engineered to analyze and interpret visual information like their linguistic counterparts interpret text. Drawing on extensive visual datasets, LVLMs are adept at identifying and understanding visual elements and structures, thereby enabling a wide array of applications, including image-based dialogue, image recognition, visual question answering, document analysis, and image captioning.

The ascent of LVLMs follows the initial breakthroughs made by LLMs between 2017 and 2024, as illustrated in Figure 1. One of the first releases of LVLMs with pioneering models is CLIP, released by OpenAI (2021). CLIP, a vision-language model, excels in tasks ranging from image captioning to visual question answering and image retrieval by leveraging its dual understanding of images and text. The advent of GPT-4 (Generative Pre-trained Transformers) by OpenAI marked a significant milestone with its enhanced generative capabilities (OpenAI, 2023a). In September 2023, OpenAI expanded these capabilities by introducing multi-modal functions to ChatGPT titled GPT-4 Vision (GPT-4V), allowing the model to process and respond to visual and auditory data (OpenAI, 2023b). GPT-4V extends the robust capabilities of GPT-4 to include visual analysis, offering a more holistic interaction experience. This multi-modal integration provides new opportunities for various industries to harness AI in unprecedented ways.

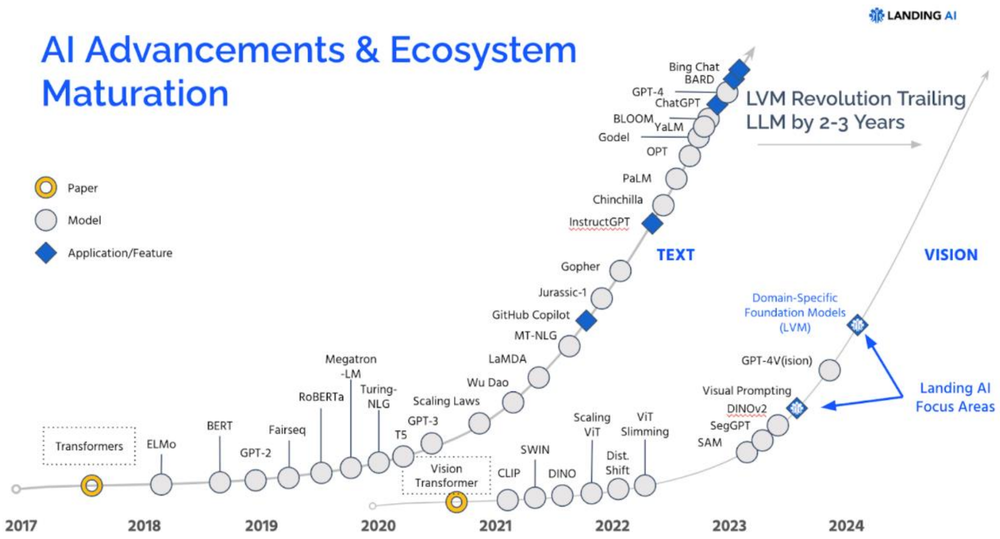

Figure 1: LVM and LVLM progress (LandingAI, 2023).

Applications of GPT-4 Vision span numerous sectors, including healthcare, robotics, security and surveillance, retail and commerce, as well as content creation and entertainment, demonstrating its versatility and broad utility. This introductory exploration sets the stage for a detailed investigation into the applications of GPT-4 Vision, focusing on the construction industry—a field where the potential of such technologies has not yet been fully tapped. This study aims to reveal the applications of GPT-4 Vision in construction, highlighting its potential in progress monitoring and tracking. As this topic is delved into more deeply, the capabilities and challenges of integrating AI in construction will be explored, providing a comprehensive overview of how these technological advancements could reshape the industry.

Related Work

The integration of artificial intelligence in various sectors has reached new heights with the advent of GPT-4V, OpenAI's most advanced generative model. This section delves into the diverse applications of GPT-4V across different domains, demonstrating its capability to interpret and respond to visual data alongside text. From transforming medical diagnostics to advancing remote sensing technologies, the applications of this AI tool exemplify a significant leap in bridging the gap between visual perception and language understanding.

In a 2024 study by Sievert et al., the researchers explored how OpenAI's ChatGPT 4 with Vision capabilities could be used to analyze medical images, specifically confocal laser endomicroscopy (CLE) images, for diagnosing a type of cancer that occurs in the throat. A collection of 12,809 CLE images from five patients was gathered and anonymized. The images were used to train and validate OpenAI's GPT-4.0 API. A training dataset of 16 images and a validation dataset of 139 images were classified. Despite the limited training, GPT-4.0 achieved an accuracy of 71.2% in identifying cancer, which was still below the 88.5% accuracy rate of human medical experts. This discrepancy highlights the challenges and limitations of AI in medical diagnostics, mainly when dealing with small datasets (Sievert et al., 2024). In a correspondence to the editor of the International Journal of Surgery (London, England), the potential of GPT-4 in altering breast cancer treatment is highlighted. The authors discuss how this advanced AI technology can aid in interpreting complex medical concepts, providing emotional support, and assisting in patient self-management, making it a critical component of breast cancer care. While GPT-4 enhances decision-making and medical education for healthcare providers, it is emphasized that it cannot replace the crucial role of human doctors or the empathy inherent in patient care. Breast cancer treatment still demands expert judgment and a personalized approach from a physician, and ethical considerations are vital to ensure fairness and transparency in AI's application. Despite potential challenges, there is significant optimism about the role of GPT-4 in advancing breast cancer treatment, promising a future where human expertise and artificial intelligence synergize to enhance patient support and care. The correspondence calls for further research to explore the benefits of GPT-4, underscoring its potential to transform healthcare practices (Deng et al., 2023).

Recent advancements in AI technology have led to exploring its potential applications in medical education, particularly in examining how models like ChatGPT perform in medical examinations. In a 2024 study by Nakao et al., researchers assessed GPT-4V using the 117th Japanese National Medical Licensing Examination, which included visual elements. The study revealed that the inclusion of images did not improve performance; accuracy rates were 68% with images and 72% without, suggesting that the current version of GPT-4V may struggle with interpreting medical images, potentially limiting its applicability in medical training and decision-making (Nakao et al., 2024). Building on these findings, another study by Hyungjin Kim et al. in 2024 explicitly focused on ChatGPT's ability to interpret radiological images from medical school exam questions. While ChatGPT demonstrated proficiency in handling text-based radiology questions, it weakened with image-based queries, showing significantly lower accuracy than third-year medical students. This indicates that although AI models like ChatGPT are progressing, they still require significant enhancements and specialized training in medical imaging to be considered reliable in the clinical radiology setting (Kim et al., 2024).

Despite this technology's challenges and early development stage, the authors are optimistic about its application prospects, suggesting that Visual ChatGPT could significantly advance remote sensing methodologies by making them more accessible and efficient. Balado and Nguyen (2023) evaluated the functionality of MATLAB codes generated by ChatGPT for point cloud processing tasks such as surface normal calculation, curvature, eigenvalues, and eigenfeatures. The study demonstrated that while ChatGPT could generate simple and short functional codes, it struggled with more complex code that required the correct use of loops, indexes, or equations. This research highlights the potential of LLMs in generating code for specific tasks, suggesting their utility primarily in educational contexts or as a starting point for more complex programming challenges.

ChatGPT-4's vision capabilities have not been thoroughly explored in construction applications, with only a few review papers discussing the potential usage of these vision applications. The 2024 article by Ghimire, Kim, and Acharya explores the role of Generative AI in the construction industry, focusing on its opportunities and challenges. While their discussion primarily addresses text-to-text applications, they also briefly mention text-to-image applications. These potential uses involve generating visual representations of site conditions, traffic patterns, and zoning laws and creating targeted safety and trade training materials. However, the article lacks examples of image-to-text applications (Ghimire et al., 2024). In another study, Saka et al. (2024) comprehensively examine GPTs within the construction industry, exploring their potential applications, limitations, and practical utility. They highlight two specific computer vision capabilities of GPTs: hazard identification and waste management. The authors include an image of a hazardous construction site environment to prompt the identification of potential hazards. Another example demonstrated the use of ChatGPT to identify waste materials in an image and recommend appropriate waste management methods, with ChatGPT providing effective responses. Together, these studies reflect the growing interest in applying advanced AI tools to bridge technological gaps and enhance operational efficiencies in the construction industry.

An Illustrative Example

This section demonstrates the application of GPT-4 Vision to monitor and track construction progress for two buildings on a university campus at the Middle East Technical University. The first site features a combination of reinforced and steel structures (Figure 2a), while the second site consists of fully reinforced concrete structures (Figure 2b). ChatGPT had been used via chat.openai.com as of April 28th, 2024. We used high-resolution aerial photographs with dimensions of 4000x3000 pixels. No custom instructions of ChatGPT or memorization features were enabled, allowing results based purely on the input provided during each session. The response time for each result generation was less than 30 seconds.

(a) (b)

Figure 2: Input images for scene understanding.

For the initial analysis, High-resolution aerial images measuring 4000x3000 pixels were utilized. The AI was prompted to *"List the properties in this construction site."* for each image, ChatGPT responded to for reinforced and steel structure (Figure 2a) as:

> *In the construction site depicted in the image, the following properties and features can be identified:*
> ***1. Building Under Construction****: A partially constructed multistory building with exposed floors.*
> ***2. Red Steel Framework:*** *A red steel structural framework is visible on top of the building, indicating ongoing construction or expansion.*
> ***3. Heavy Machinery:***
> *• Excavator: Positioned on the ground to the right of the building, possibly used for earthmoving or site preparation tasks.*
> *• Wheel Loader or similar machinery: Located at the bottom left corner, typically used for moving materials.*
> ***4. Construction Materials:***
> *• Sand piles: Likely used for making concrete or for grading purposes.*
> *• Gravel or aggregate piles: Also a component of concrete or used for drainage systems.*
> *• Pipes and construction supplies: Stored around the site, indicating the various stages of construction activity.*
> ***5. Perimeter Fencing:*** *Enclosing the site for security and safety, indicating a controlled access area.*
> ***6. Storage and Workspace:***
> *• Covered areas that could serve as on-site storage for tools and materials or as workspaces for the construction crew.*
> *• Open areas with stacked materials and supplies necessary for the ongoing construction work.*
> ***7. Geographic Location:*** *The presence of a forest or treed area around the construction site, suggesting a location that is not densely urban.*
> ***8. Site Terrain:*** *Modified ground surrounding the building, with visible tire tracks and dug-out areas indicating heavy machinery movement and site preparation work.*
> ***9. Safety Features****: Visible safety barriers around potential hazards and possibly safety signage (not clearly visible but commonly present in such settings).*

ChatGPT response for fully reinforced concrete structure (Figure 2b):

> *The image shows a construction site with various features:*
> ***1. Partially Constructed Multi-Story Building****: There's a structure that appears to be a multi-story concrete building in the midst of construction. Some floors are partially done with visible columns and support beams.*
> ***2. Construction Materials:*** *Various construction materials are scattered throughout the site, including stacks of bricks, piles of construction bars (rebar), and other building materials.*
> ***3. Heavy Machinery:*** *There is construction machinery present, which includes at least one telehandler and what appears to be a mobile crane.*
> ***4. Scaffolding:*** *There are sections of scaffolding around the building, used by workers to access higher levels of the construction.*
> ***5. Debris:*** *There's a significant amount of debris and rubble on the upper floors of the building, possibly from demolition work or the aftermath of a structural collapse.*
> ***6. Surrounding Structures:*** *Adjacent to the construction site, there are other buildings that look like completed structures, possibly office or industrial buildings.*
> ***7. Safety Barriers****: There are red and white safety barriers around the perimeter of the site, which are likely there to prevent unauthorized access and to mark the construction zone.*
> ***8. Construction Site Accessories:*** *There are also various items like portable toilets, storage containers, and makeshift sheds, probably used for storage or as temporary site offices.*
> ***9. Fenced Areas:*** *Part of the construction site is fenced, likely for security purposes and to delineate the construction area from the surrounding environment.*
> ***10. Topography****: The site is surrounded by some greenery and trees, indicating it may be on the outskirts of an urban area or in a more suburban or rural setting.*
> ***11. Vehicle Tracks:*** *There are visible tracks on the ground, indicating the movement of vehicles around the site.*
> *These observations provide a general understanding of the construction site's characteristics and status.*

These results showcase GPT-4 Vision's adeptness at comprehensive scene analysis, providing a foundational understanding of the construction site's current state and context. Following the scene understanding, the study progressed to examine GPT-4 Vision's capability in tracking construction development and assessing task completion. Two sets of aerial images of the fully reinforced concrete structure, taken one month apart, were uploaded to the ChatGPT (Figure 3). The system was instructed to *"Two images will be uploaded, after upload, categorize and create a list of construction progress."*

Figure 3: Input images for construction progress tracking.

ChatGPT responded to this prompt as given below:

> *Thank you for uploading both images. Based on the visual information, I will categorize the construction progress as follows:*
> ***First Image:***
> *1. Excavation and foundation work appears to be complete.*
> *2. Formwork for columns and walls is erected, indicating that the construction is prepared for concrete pouring.*
> *3. Scaffolding is in place for work on the above-ground structure.*
> *4. Construction materials and equipment are organized around the site, showing active work. 5. The ground floor slab seems to be complete, with work progressing on upper floor slabs.*
> ***Second Image:***
> *1. The progress is similar to the first image with the continuation of concrete work.*
> *2. Formwork is present on additional floors, suggesting vertical construction progression. 3. More scaffolding is visible, indicating ongoing work on higher levels.*
> *4. Construction materials appear to be more spread out, likely due to work taking place on various parts of the building simultaneously.*
> *5. The perimeter of the building seems to be more defined, with potential work on internal partitions or walls.*
> *Both images show the construction site at an advanced stage of the structural phase, with work focused on erecting the concrete skeleton of the building. The precise sequence of construction steps can only be determined if the images are taken at different times; however, the visible elements suggest the project is moving from completing the ground floor toward constructing the upper floors. There doesn't appear to be any significant exterior work yet, such as cladding or facade installation, which typically follows the completion of the main structure.*

Then, the AI tool was provided with a list of expected tasks at the construction site and asked to, *"From this list which tasks are completed? Categorize, completed, ongoing and not started tasks only. Prepare a table.*
1 Site - Earth
2 Foundations
3 Structural Columns - B1 Basement

4 Structural framing - B1 Basement
5 Floor Slabs - B1 Basement
6 Structural Framing - Ground Floor
7 Floor Slabs - Ground Floor
8 Structural Columns - Ground Floor
9 Columns - Ground Floor
10 Structural Framing - 1st Floor
11 Floor Slabs - 1st Floor
12 Structural Columns - 1st Floor
13 Columns - 1st Floor
14 Structural Framing - 2nd Floor
15 Floor Slabs - 2nd Floor
16 Structural Columns - 2nd Floor
17 Columns - 2nd Floor
18 Structural Framing - Roof
19 Floor Slabs - Roof
20 Roofs"

GPT-4 Vision identified the progress and tabulated the tasks into categories as below:

> *Based on the images provided and the construction list, the categorization of tasks is as follows:*
> *1 Site - Earth - Completed*
> *2 Foundations - Completed*
> *3 Structural Columns - B1 Basement - Completed*
> *4 Structural framing - B1 Basement - Completed*
> *5 Floor Slabs - B1 Basement - Completed*
> *6 Structural Framing - Ground Floor - Completed*
> *7 Floor Slabs - Ground Floor - Completed*
> *8 Structural Columns - Ground Floor - Completed*
> *9 Columns - Ground Floor - Completed*
> *10 Structural Framing - 1st Floor – Ongoing*
> *11 Floor Slabs - 1st Floor – Ongoing*
> *12 Structural Columns - 1st Floor – Ongoing*
> *13 Columns - 1st Floor – Ongoing*
> *14 Structural Framing - 2nd Floor – Not Started*
> *15 Floor Slabs - 2nd Floor – Not Started*
> *16 Structural Columns - 2nd Floor – Not Started*
> *17 Columns - 2nd Floor – Not Started*
> *18 Structural Framing - Roof – Not Started*
> *19 Floor Slabs - Roof – Not Started*
> *20 Roofs – Not Started*
> *The above categorization is inferred from the images with the understanding that the first floor is above the ground floor. The tasks that are 'Ongoing' are assumed because there is visible work in progress related to those tasks in the images, whereas 'Not Started' tasks are those for which there is no visible work or structure present.*

Discussion and Conclusions

The deployment of GPT-4 Vision in construction progress monitoring offers promising insights into the initial capabilities of AI for scene understanding and progress monitoring. As far as the authors' knowledge, this is the first study to explore the use of GPT-4 Vision for construction progress monitoring, offering new insights into its capabilities and limitations. This section delves into the findings of this evaluation in detail while explaining the current state, limitations, opportunities, and future works.

Current State and Limitations

- The review of ChatGPT-4 Vision capabilities in identifying and analyzing construction sites reveals both its strengths and limitations. Initially, ChatGPT effectively recognizes the type of building and construction materials, correctly identifying type of steel and reinforced concrete structures.
- Regarding construction machinery, ChatGPT demonstrates an understanding of different equipment types, such as excavators and wheel loaders, although it struggles with precise location identification due to its inability to detect objects at the pixel level. The inability to accurately detect objects in images hinders the performance of detection and segmentation tasks in computer vision applications. The machinery was identified as a telehandler and a mobile crane in Figure 2b. Although the mobile crane was correctly identified, a backhoe loader was actually present on the site instead of a telehandler. However, the equipment mounted on the front of the backhoe loader is similar to that of a telehandler, which performs similar functions. Therefore, this misclassification is not entirely incorrect.
- Moreover, ChatGPT can identify various construction site materials like sand piles, pipes, and other supplies, providing relevant information about their uses. This knowledge aids in assessing the progress of construction accurately. However, there are instances of misclassification, such as wrongly identifying debris on upper floors as unused materials, leading to incorrect assumptions about potential demolition work. This points to limitations in object classification that could affect the model's reliability in specific scenarios.
- Regarding safety measures, ChatGPT identifies general precautions like perimeter fencing and safety barriers but lacks specificity about their locations. This general information might not be sufficient for detailed safety analysis or planning.
- ChatGPT demonstrates proficiency in contextualizing the construction environment, successfully identifying non-urban settings by noting surrounding forests and tree areas. It recognizes site accessories such as portable toilets and storage containers, which are crucial for managing and organizing construction sites. The model also comments on site accessibility by noting roads and visible tracks, although these observations are not detailed.
- For the comparison of consecutive time images, ChatGPT analyzes each construction stage sequentially, providing general information about the stage, materials, and machinery involved as it conducts scene understanding (Figure 3). The first image was identified with the foundation work completed. ChatGPT noted the preparation for concrete pouring, inferred from the erection of formwork for columns and walls. It correctly identified the completion of the ground floor slab. The addition of floors and the progression of vertical construction was recognized in the second image. It was also observed that more construction materials were distributed across the site, indicating that various parts of the structure were being built simultaneously.
- To establish a baseline for ChatGPT, items from the construction plan were provided, and it was prompted to categorize these items as completed, ongoing, or not started. It demonstrated the ability to create a categorized table. ChatGPT accurately understood that the earthworks and foundations were completed. The platform identified the floor levels, noting that the tasks on the ground floor were completed and that construction

on the first floor was ongoing. The tasks for the second floor had not yet started. A more detailed construction plan could be input to enhance the categorization of each task.

Opportunities and Future Works

- Looking forward, the development of GPT-4V in progress monitoring tasks represents an early step with significant potential for expansion and improvement. Current research should include more diverse structures, such as transportation and hydraulic facilities, to test the model's capability to identify different material types. This would provide a broader understanding of its applicability across various construction domains.
- Integrating aerial and ground images when uploading to the ChatGPT process could enhance the model's effectiveness by providing a more comprehensive view of construction sites. This approach could lead to more detailed and accurate monitoring, encompassing a wider range of perspectives and details.
- While current GPT models do not have the capability to segment objects within images, utilizing pre-segmented images could facilitate better object differentiation, as suggested by Yang et al. (2023), indicating that segmented images improve object localization. Hence, incorporating segmented images could be a valuable next step in refining GPT’s visual recognition functions.
- It is also crucial to evaluate other language vision models like Gemini (Google, 2023) and LLaVa (Liu et al., 2023) to compare their performance with GPT-4V. Such comparative studies could highlight strengths and weaknesses specific to each model, guiding further development and optimization.
- Integrating GPT models with as-planned models could significantly enhance construction monitoring, such as exporting screenshots of the same viewpoints from 4D BIM as both as-planned and as-built images for GPT analysis. This integration could assist in creating accurate digital twins and enable precise tracking of construction progress.
- Lastly, there is immense potential in training or fine-tuning these models with construction-specific images. Domain-specific large vision models could revolutionize the industry by improving efficiency and expanding capabilities (LandingAI, 2023). Their ability to understand complex patterns from large datasets could be pivotal in addressing various challenges within the construction sector and beyond.

References

Balado, J., & Nguyen, G. (2023). Chatgpt for Point Cloud 3D Object Processing. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *10*(1-W1-2023), 107–114. https://doi.org/10.5194/isprs-annals-X-1-W1-2023-107-2023

Deng, L., Zhang, Y., Luo, S., & Xu, J. (2023). GPT-4 in breast cancer combat: a dazzling leap forward or merely a whim? *International Journal of Surgery (London, England)*, *109*(11), 3732–3735. https://doi.org/10.1097/JS9.0000000000000668

Ghimire, P., Kim, K., & Acharya, M. (2024). Opportunities and Challenges of Generative AI in Construction Industry: Focusing on Adoption of Text-Based Models. *Buildings*, *14*(1). https://doi.org/10.3390/buildings14010220

Google. (2023). *Introducing Gemini: our largest and most capable AI model*. https://blog.google/technology/ai/google-gemini-ai/

Kim, H., Kim, P., Joo, I., Kim, J. H., Park, C. M., & Yoon, S. H. (2024). ChatGPT Vision for Radiological Interpretation: An Investigation Using Medical School Radiology Examinations. *Korean Journal of Radiology*, *25*(4), 403–406. https://doi.org/10.3348/kjr.2024.0017

LandingAI. (2023). *Introducing Domain-Specific Large Vision Models*. https://landing.ai/blog/introducing-domain-specific-large-vision-models

Liu, H., Li, C., Wu, Q., & Lee, Y. J. (2023). Visual Instruction Tuning. *ArXiv Preprint*.

Nakao, T., Miki, S., Nakamura, Y., Kikuchi, T., Nomura, Y., Hanaoka, S., Yoshikawa, T., & Abe, O. (2024). Capability of GPT-4V(ision) in the Japanese National Medical Licensing Examination: Evaluation Study. *JMIR Medical Education, 10,* e54393. https://doi.org/10.2196/54393

OpenAI. (2021). *CLIP: Connecting text and images*. https://openai.com/research/clip

OpenAI. (2022). *Introducing ChatGPT*. https://openai.com/blog/chatgpt

OpenAI. (2023a). *GPT-4 is OpenAI's most advanced system, producing safer and more useful responses*. https://openai.com/gpt-4

OpenAI. (2023b). *GPT-4V(ision) system card*. https://openai.com/research/gpt-4v-system-card

Saka, A., Taiwo, R., Saka, N., Salami, B. A., Ajayi, S., Akande, K., & Kazemi, H. (2024). GPT models in construction industry: Opportunities, limitations, and a use case validation. *Developments in the Built Environment*, *17*(2023), 100300. https://doi.org/10.1016/j.dibe.2023.100300

Sievert, M., Aubreville, M., Mueller, S. K., Eckstein, M., Breininger, K., Iro, H., & Goncalves, M. (2024). Diagnosis of malignancy in oropharyngeal confocal laser endomicroscopy using GPT 4.0 with vision. *European Archives of Oto-Rhino-Laryngology*, *281*(4), 2115–2122. https://doi.org/10.1007/s00405-024-08476-5

Yang, J., Zhang, H., Li, F., Zou, X., Li, C., & Gao, J. (2023). Set-of-Mark Prompting Unleashes Extraordinary Visual Grounding in GPT-4V. *ArXiv Preprint*, 1–23.

A Review of BIM-Based Sustainability Applications in the Construction Industry

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Abstract

The rapid growth in global population and technological advancements has led to a significant increase in human needs and consumption rates, resulting in critical levels of energy resources. According to data from 2021, the construction industry is the sector with the highest energy use and CO2 emissions, accounting for approximately 40% of global consumption. Consequently, there has been a heightened interest in sustainability within the construction industry, with numerous studies conducted on the subject. Many of these studies emphasize the advantages of integrating BIM into sustainability studies, such as collecting and sharing information, saving time, and minimizing errors. This study aims to increase understanding of BIM-based sustainability applications in construction projects, identify gaps in existing literature, and determine future research trends. To achieve these objectives, a comprehensive literature review was conducted on BIM-based sustainability applications in the construction industry over the past decade. The study concludes with a summary of academic research on Green BIM, identification of gaps in the literature, and forecasting of future trends. The research findings indicate that the Green BIM concept has gained broader appeal since 2019, and its use in conjunction with IoT, digital twin, and Industry 4.0 concepts has increased. This suggests that future studies on Green BIM should involve interdisciplinary research in fields such as engineering, business, economics, and information technologies, with a focus on facility management processes and the integration of sustainability and AI technologies. Currently, there are very few studies that take a comprehensive approach to addressing all dimensions of sustainability. As models that incorporate both environmental and economic aspects become more prevalent, the adoption of BIM-supported sustainability applications has begun in the sector, but the desired level of usage has not yet been achieved.

Keywords: *BIM, building information modeling, construction industry, Green BIM, sustainability.*

Introduction

The unprecedented growth in global population, industrialization, and urbanization has exerted immense pressure on the climate, biodiversity, natural resources, and urban green spaces, leading to their increasing scarcity and pollution. The development of transportation networks and vehicles in urban areas has resulted in several issues, including excessive energy consumption, traffic congestion, and air and noise pollution (Açıl, 2022; Mersal, 2016). The expanding technology and energy demands have contributed to environmental pollution and the depletion of fossil fuel reserves at an alarming rate. Uncontrolled development not only undermines the gains made but also threatens the fundamental ecosystem balance (Harris, 2000).

In 2022, a global status report on the building and construction sector revealed that the construction industry accounts for approximately 38% of global energy consumption and 42% of greenhouse gas emissions. The construction sector also accounts for a considerable portion of Turkey's energy consumption. As a country dependent on non-renewable energy resources, Turkey imports fossil fuels to fulfill its energy requirements. In 2019, 41.6 billion dollars of Turkey's total imports consisted of primary energy resources, amounting to 19.8% of the total. This situation also has a detrimental impact on the country's economy (Gülaçmaz, 2021). Buildings must be designed with energy consumption and CO_2 emissions in mind at every stage of their existence, spanning from design and construction to operation and demolition. While new buildings can be constructed to meet energy-efficient design criteria, existing buildings can also be retrofitted to become energy-efficient buildings through the use of active and passive systems. The process of designing or transforming buildings into environmentally friendly green buildings is intricate and requires expertise in numerous fields. Furthermore, the distinct nature of construction projects, the difficulty in quantifying parameters such as energy use, greenhouse gas emissions, and waste production, and the substantial degree of uncertainty in future calculations, all serve to complicate the entire green building process, from design to demolition.

Utilizing Building Information Modeling (BIM) technology, it is possible to generate three-dimensional models of buildings during the design phase and perform energy analysis by projecting the amount of energy required throughout the building's lifetime. This enables the conservation and utilization of on-site energy, which is a crucial indicator of development and contributes to environmental protection. By ensuring energy efficiency for buildings that have the highest energy demands, BIM technology helps to reduce energy consumption. The concept of employing BIM-based sustainable design and green building applications to achieve sustainable objectives in a project is referred to as "Green BIM." In response to global warming, energy resource scarcity, and environmental degradation, Green BIM serves as a valuable tool for constructing low-carbon eco-cities. Many researchers agree that BIM technology can simplify complex processes for individuals and organizations in the construction industry. The goal of this study is to examine the existing literature on academic studies that involve sustainability and BIM integration. The research aims to identify gaps in the literature on green BIM, a concept that refers to the use of BIM in sustainable construction. To achieve this, articles were scanned using the WOS (Web of Science) database, using keywords such as green BIM, sustainability, sustainable construction, construction industry, and BIM. The selected articles were filtered based on their relevance to green BIM and their potential to contribute to the study. A bibliometric analysis was then conducted on the selected articles to determine trends and identify gaps in the literature. The study's findings are expected to provide researchers and experts in the field with a comprehensive understanding of the scope of BIM's application for sustainable construction and to promote a holistic BIM approach for sustainable design and construction as a green BIM.

The construction industry's significant impact on resource consumption, energy use, CO_2 emissions, air and environmental pollution makes reducing its negative effects on the environment a top priority environmental problem. Numerous studies have extensively examined the use of BIM in all stages of construction projects, from design to demolition, and have found it to significantly contribute to project sustainability. This study aims to systematically review the literature on the "Green BIM" concept, which integrates sustainability and BIM issues, in order to summarize existing research, identify knowledge gaps, and determine future research directions. A bibliometric analysis technique was employed in this study to analyze academic publications related to the Green BIM concept.

Methodology

Within the scope of the study, the data to be used for bibliometric analysis were collected through the Web of Science (WOS) library. First, the word groups "Green BIM" and "Sustainability and BIM" were searched separately through the WOS database using article titles, keywords and article topics. The search outcomes were filtered to encompass the years 2012-2022 and only include research and review articles, resulting in a total of 832 articles found. In this study, the VOSviewer software was chosen for its ability to perform basic functions effectively. This program provides cluster-based maps that enable easy classification of bibliometric network data. To map the 832 articles accessed, Citation and Co-occurrence analyses were conducted. As a result, documents, sources, authors, and countries were identified under citation analysis, while keywords were mapped under co-occurrence analysis.

Findings and Discussion

Sustainability has emerged as a critical concern in the contemporary construction industry, primarily driven by the pressing issues of global warming, energy resource depletion, and environmental degradation (Harvey, 2012). In this context, Green BIM is widely recognized as an effective tool for promoting eco-friendly building design, energy efficiency, and natural resource conservation. The primary goal of this study is to investigate the current trends in Green BIM by analyzing the theoretical underpinnings of the Green BIM concept and the relevant research conducted over the past decade, while also assessing the bibliometric properties. After employing the appropriate filters for the research topic, a total of 832 research and review articles were identified in the WOS database. These publications were filtered by year to include only those published between 2012-2022 and were limited to research and review articles. Furthermore, a second search was conducted using the subjects "BIM" and "Green Building" between 2012-2022, providing a comparative view of the number of studies on these topics. The results indicate that while the overall number of studies on BIM has increased over the years, there has been a decrease in recent years. In contrast, there has been a significant increase in studies on green building, particularly between 2018-2020, but this trend has since slowed or decreased. Comparing the number of studies on green building and BIM reveals that there are fewer studies on Green BIM, and interest in this concept has remained strong since 2018.

Table 1. Top 10 journals with the most articles published on green BIM concepts.

Journals	**Number of Articles**		
	BIM	**Green Building**	**Green BIM**
Sustainability	125	216	111
Journal of Cleaner Production	45	110	40
Buildings	119	74	38
Automation in Construction	386	13	35
Journal of Building Engineering	51	39	29

Table 1 continued

Journals	Number of Articles		
	BIM	Green Building	Green BIM
Engineering Construction and Architectural Management	95	18	22
Sustainable Cities and Society	16	57	19
Building and Environment	34	112	19
Energy and Buildings	33	104	18
Applied Sciences	87	13	16

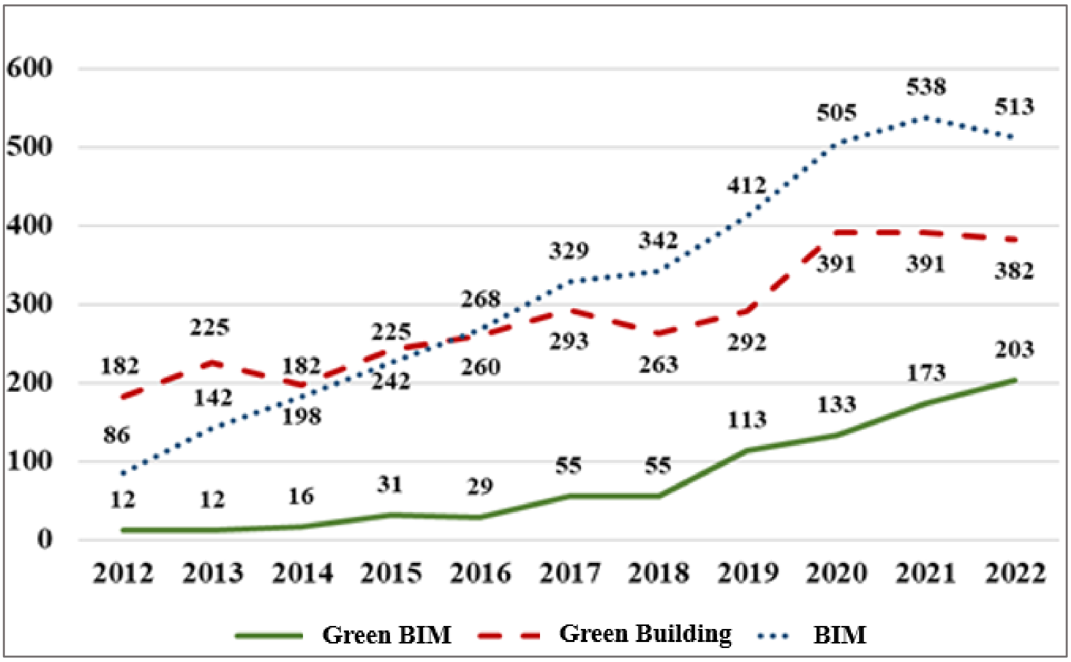

Figure 1: Number of articles on Green BIM between 2012 and 2022.

The top three journals with the most publications on Green BIM are Sustainability, Journal of Cleaner Production, and Buildings. According to Table 1, these journals have published a total of 111, 40, and 38 articles on the subject in the last 10 years, respectively. Additionally, the number of studies on BIM and Green Building published in these journals between 2012 and 2022 is also shown in the Table 1. The three articles with the highest number of citations were identified as "Application of Life-Cycle Assessment To Early Stage Building Design for Reduced Embodied Environmental Impacts" (Basbagill et al., 2013), "A Scientometric Review of Global Research on Sustainability and Sustainable Development" (Olawumi & Chan, 2018) and "Enhancing Environmental Sustainability Over Building Life Cycles Through Green BIM: A Review" (Wong & Zhou, 2015). Upon analyzing the top 10 studies with the highest number of citations, it was observed that 50% were research articles, and two of the top three articles were review articles (Table 2).

Table 2. Top 10 articles with the highest number of citations among studies on Green BIM between 2012-2022.

Author	Year	Article Title	Article Type	Number of citation
Basbagill et. al.	2013	Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts	Research	348
Olawumi and Chan	2018	A scientometric review of global research on sustainability and sustainable development	Review	314
Wong and Zhou	2015	Enhancing environmental sustainability over building life cycles through green BIM: A review	Review	304
Wang et. al.	2015	Automatic BIM component extraction from point clouds of existing buildings for sustainability applications	Research	241
Lu et. al.	2017	Building Information Modeling (BIM) for green buildings: A critical review and future directions	Review	224
Soust-Verdaguer et. al.	2017	Critical review of bim-based LCA method to buildings	Review	214
Chong et. al.	2017	A mixed review of the adoption of Building Information Modelling (BIM) for sustainability	Review	190
Cheng and Ma	2013	A BIM-based system for demolition and renovation waste estimation and planning	Research	189
Abanda and Byers	2016	An investigation of the impact of building orientation on energy consumption in a domestic building using emerging BIM (Building Information Modelling)	Research	173
Bynum et. al.	2013	Building Information Modeling in Support of Sustainable Design and Construction	Research	134

During the period from 2012 to 2022, the ranking of sources based on the number of citations received by articles published on Green BIM is presented in Table 3. The top three journals in terms of the number of citations received are Automation in Construction, Journal of Cleaner Production, and Sustainability journals. However, when considering the citation/article ratio, it is evident that the top three journals are Automation in Construction, Journal of Cleaner Production, and Energy and Buildings, respectively.

Table 3. List of top 10 journals where articles on Green BIM with the highest number of citations were published between 2012 and 2022.

Journal	Number of Articles	Number of Citations
Automation in Construction	35	2294
Journal of Cleaner Production	40	2165
Sustainability	111	1413
Building and Environment	19	889
Energy and Buildings	18	856
Journal of Building Engineering	29	847
Sustainable Cities and Society	19	792
Renewable & Sustainable Energy Reviews	9	373
Engineering Construction and Architectural Management	22	348
Buildings	38	346

The top twenty most frequently cited authors among those who have published research on the Green BIM concept and related subjects are presented in Table 4, organized according to the number of citations their work has received. In the ranking based on the citations garnered from their Green BIM-related studies, Daniel W. M. Chan takes the lead with 1106 citations from a total of 22 articles. Trailing closely behind in second place is Timothy O. Olawumi, with 987 citations from 18 articles. Rounding out the top three is Xiangyu Wang, who has authored 9 articles on Green BIM and received 527 citations.

Table 4. The top 20 authors with the most citations based on their Green BIM-themed articles published between 2012 and 2022.

Author	**Article**	**Citation**	**Link**	**Author**	**Article**	**Citation**	**Link**
Chan, Daniel W. M.	22	1106	483	Chan, Albert P. C.	4	284	84
Olawumi, Timothy O.	18	987	443	Lu, Yujie	3	283	142
Wang, Xiangyu	9	527	143	Llatas, Carmen	4	277	137
Cheng, Jack C. P.	6	405	54	Soust-Verdaguer, Bernardette	4	277	137
Jalaei, Farzad	7	402	197	Figueiredo, Karoline	5	261	144
Chong, Heap-Yih	5	315	106	Abanda, F. H.	6	257	71
Jrade, Ahmad	4	311	165	Hollberg, Alexander	4	226	123
Haddad, Assed	7	299	174	Shadram, Farshid	3	222	78
Jin, Ruoyu	5	296	48	Habert, Guillaume	3	221	107
Kaewunruen, Sakdirat	8	290	58	Passer, Alexander	5	218	144

Table 5 presents the country ranking and mapping based on citation numbers. In the country-based ranking, which is based on the number of citations of studies on sustainability and BIM integration in the construction industry over the past 10 years, China, England, the USA, and Australia are in the top four positions, consistent with the institution ranking. Turkey ranks 20th in the list, with 21 studies and 280 citations to those studies.

Table 5. The top 20 countries with the most citations for their Green BIM-themed articles between 2012 and 2022.

Country	**Articles**	**Citations**	**Links**	**Country**	**Articles**	**Citations**	**Links**
China	224	5603	2273	Iran	29	513	388
England	116	2715	1129	Italy	37	509	314
USA	76	2382	874	Malaysia	53	475	622
Australia	88	2217	1381	Egypt	28	378	288
South Korea	27	997	359	Sweden	14	376	220
Canada	28	817	541	Ireland	6	340	72
Spain	36	722	499	Netherlands	15	339	197
Portugal	25	610	570	Austria	14	320	280
Brazil	27	522	504	Germany	27	292	121
Singapur	17	519	340	Turkey	21	280	317

To be included in the analysis, keywords were required to have a minimum of ten occurrences, resulting in 120 out of 3322 keywords meeting these criteria. The keywords with the highest visibility, as determined by frequency of occurrence, are presented in Table 6. As illustrated in Figure 2, the keyword "energy," in its various combinations, is the most fundamental parameter in green BIM research.

Table 6. The most used keywords in their articles on Green BIM between 2012 and 2022.

Keywords	**Co-occur**	**Links**	**Keywords**	**Co-occur**	**Links**
BIM	492	771	Environmental Impact/ Analysis	35	93
Sustainability	185	402	Integration	25	62
LCA	93	230	Circular economy	24	64
Energy Performance/Analysis/Efficiency	87	186	Digital twin	19	40
Sustainable Construction	71	178	Green BIM	17	31
Construction Projects	70	154	Construction Management	17	36
Green building	65	131	Lean Construction	15	37
Literature review	56	131	Carbon Emission/Carbon Footprint	15	35
Sustainable design	40	104	Facility Management/Care	15	23
Building	36	90	Interoperability	14	27

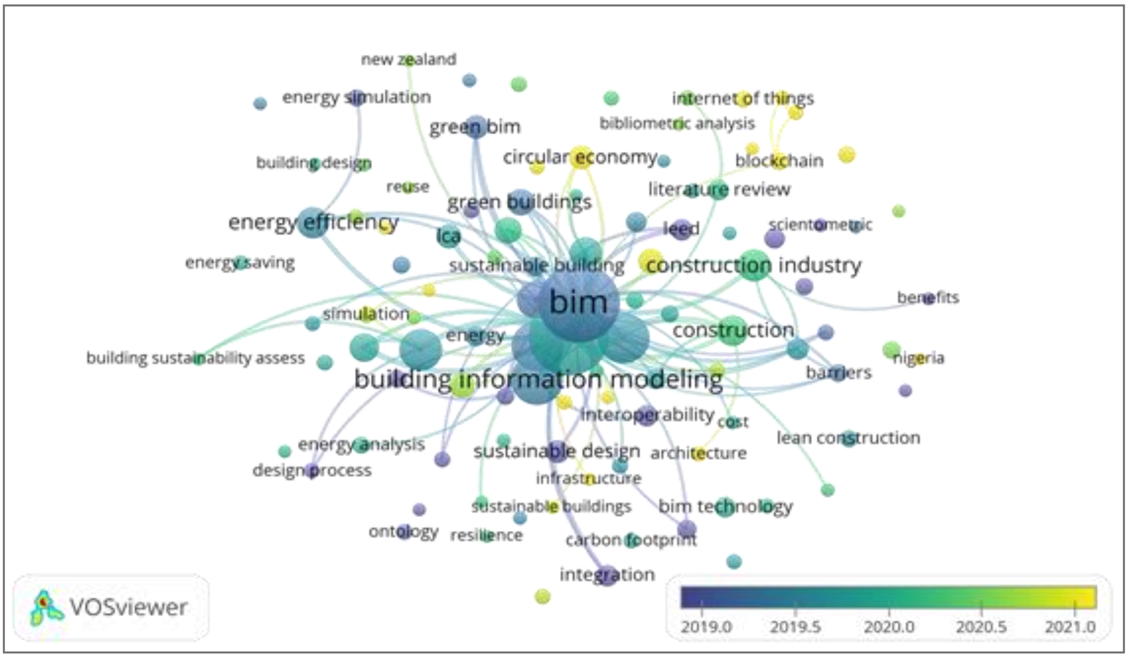

Figure 2: Keyword in the mapping system based on co-occurrence data.

The findings from the bibliometric analysis conducted using co-occurrence data reveal that the Green BIM concept has gained prominence in studies on sustainability and BIM integration since 2019. It is noteworthy that the keywords facility management, maintenance, digital twin, internet of things, Blockchain, and Industry 4.0 have witnessed an upsurge in usage in recent times. As such, it is expected that future research in the field of Green BIM will involve extensive interdisciplinary studies in the domain of engineering, business, economics, and information technologies, encompassing facility management processes and the integration of sustainability and artificial intelligence technologies.

In this section of the study, a content analysis of the most highly cited articles was performed as a result of the bibliometric analysis, with the aim of identifying the primary topics on which the most effective studies within the scope of Green BIM over the past decade have focused. Energy efficiency, Green Building Assessment Tools, and Life Cycle Analysis are the central themes of Green BIM studies. For instance, LCA-BIM-based models developed by various researchers to aid designers in the selection and sizing of building materials in green building design can be cited as examples of such studies (Basbagill et al., 2013; Figueiredo et al., 2021; Jrade & Jalaei, 2013; Najjar et al., 2017; Röck et al., 2018).

Minimizing carbon emissions from buildings is another topic that studies on sustainability and BIM integration examine. To this end, Yang et al. (2018) created a BIM-supported LCA analysis model that encompasses building material production, logistics, assembly, and construction processes. In another study, a BIM-based model was developed to optimize the life cycle costs and carbon emissions of buildings throughout their entire lifecycle (Liu et al., 2015). Unlike previous studies, Cavalliere et al. (2019) proposed a novel LCA model that increases the detail levels of BIM and LCA to guarantee continuous environmental impact analysis throughout the design process, encompassing planning, project approval, tendering, and construction phases.

Building Information Modeling (BIM) has been increasingly employed in recent years to investigate the energy efficiency and performance of buildings, owing to its expediency and ease of use for interoperability and visualization. Abanda and Byers (2016) utilized BIM in their research to analyze the impact of building orientation on energy efficiency. Shadram et al. (2016) developed a BIM-based framework model that aimed to minimize the embodied energy in building material selection. To enhance the dependability of BIM-based energy modeling Ham and Golparvar-Fard (2015), created a model that allows for the automatic association of actual heat transfer measurements, obtained using 3D thermography, with BIM elements. Furthermore, Kaewunruen et al. (2018) devised a framework model that integrates digital twin and sustainability concepts to evaluate existing buildings both technically and financially within the context of "Net Zero Energy Buildings."

BIM has also gained traction in studies focusing on waste management, which is a crucial aspect of sustainability in construction projects. Cheng and Ma (2013) developed a BIM-based model that estimates the amount of waste generated by demolition and renovation projects, taking into account the recyclability and reusability of waste. This model also accounts for the need for pickup trucks at waste facilities and provides cost estimates for waste disposal. Atta et al. (2021) made a significant contribution to waste minimization by creating a BIM-based digital material passport model that considers demountability, reuse, and recyclability factors of materials.

In various research initiatives focused on BIM and sustainability, it has been observed that green building assessment systems are frequently incorporated into the developed models. Jalaei and Jrade (2015) created a model that combines BIM and LEED certification systems to promote sustainable construction. Similarly, Marzouk et al. (2018) integrated LEED criteria into their BIM-based models to assist designers in material selection that is aligned with sustainability and allows for a stochastic life cycle cost estimation. Ilhan and Yaman (2016) developed a green building evaluation tool based on IFC, and preferred the BREEAM certification system to validate the model. In another study, a framework was established to ensure the integration of BIM into the SBTool green building evaluation system, and it was determined that 24 out of the 25 criteria could be evaluated through BIM for the SBTool PT certificate (Carvalho et al., 2019).

Although most studies conducted within the realm of Green BIM focus on model development, numerous research articles have also been published on the perception of Green BIM among various project stakeholders, barriers to its implementation, and critical success factors. In a survey conducted by Bynum et al. (2013), perceptions regarding the integration of BIM and sustainability were investigated. Based on the results of the study, it was highlighted that there are interoperability issues between BIM applications, that Green BIM applications are more suitable for integrated project delivery management, and that Green BIM outputs can be most effectively utilized in the design process. Olawumi et al. (2018) attempted to identify the obstacles to sustainability and BIM integration in their research. The main barriers were found to be the construction industry's resistance to change, difficulties in adopting innovative technologies, and the lack of understanding of the necessary processes and workflows for integration by practitioners. In another study, Olawumi and Chan (2018) identified the three most significant benefits of Green BIM applications as increased project quality and efficiency, improved building performance and energy consumption simulation capacity, and the ability to produce better designs due to the ease of creating alternative designs. Wu and Issa (2015) developed a comprehensive Green BIM process map to facilitate the integration of BIM in sustainable building projects.

Results

The findings of this study, which conducted a systematic literature review on the topic of "Green BIM," reveal that the leading countries in this field are China, England, and America. The authors with the highest number of citations are Daniel W. M. Chan, Timothy O. Olawumi, and Xiangyu Wang. The bibliometric analysis also indicates that the three most influential studies on Green BIM are "Application of Life-Cycle Assessment To Early Stage Building Design for Reduced Embodied Environmental Impacts" (Basbagill et al., 2013), "A Scientometric Review of Global Research on Sustainability and Sustainable Development" (Olawumi & Chan, 2018), and "Enhancing Environmental Sustainability Over Building Life Cycles Through Green BIM: A Review" (Wong & Zhou, 2015). The results based on co-occurrence data show that the Green BIM concept has grown in popularity in recent years, with the use of keywords such as sustainability and BIM integration becoming more common since 2019. Additionally, the study found that keywords such as facility management, maintenance, digital twin, internet of things, blockchain, and Industry 4.0 have gained increased visibility in recent years. This suggests that future research on Green BIM may involve interdisciplinary studies in fields such as engineering, business, economics, and information technologies, with a focus on facility management processes and the integration of sustainability and artificial intelligence technologies. According to the results obtained from the top 20 studies with the highest number of citations, it is evident that a significant amount of interest is focused on the development of BIM-based models that facilitate multi-alternative building design to evaluate the environmental performance of buildings. It is observed that there is a limited number of studies that address the social dimension of sustainability, compared to the studies that focus on the environmental and economic dimensions of sustainability. However, there is a scarcity of studies that integrate all dimensions of sustainability with an integrated approach. With the increasing use of models that include both the environmental and economic dimensions, the transition to BIM-supported sustainability applications has begun in the sector, but it has not yet reached the desired level of use. As a result, the obstacles to Green BIM applications in the sector and the research studies aimed at overcoming these obstacles have gained momentum in the last 10 years. There has been a considerable increase in the number of studies that involve optimization systems and life cycle analyses due to the development of databases that can be used for these purposes. With the advancements in IoT technology, sustainability studies regarding the operational processes of buildings, as well as the design and construction processes, have also gained momentum. It is anticipated that future studies will focus on the improvement of existing buildings within the scope of sustainability, maintenance and repair of green buildings, and digital twin and sustainability issues. Additionally, it is believed that research on Green BIM studies, where sustainability is discussed in an integrated manner with its environmental, economic, and social aspects, and Green BIM studies based on infrastructure projects, will contribute to eliminating the gaps in the literature.

The bibliometric analysis conducted in this study was limited to data extracted from the WOS database, which covered the period between 2012 and 2022. It is important to note that the scope of this study is limited to the data available in the WOS database and does not include any other sources. The main limitations of this research include the fact that the bibliometric analysis was conducted solely on the basis of citation and co-occurrence data, and the content analysis was limited to the 20 studies with the highest number of citations. The authors are currently working on a more comprehensive and integrated review article that will address these limitations. The findings of this study are expected to provide a basic level of guidance for research on sustainability and BIM in the construction industry, and to contribute to the identification of gaps in the literature and the determination of trends.

References

Abanda, F., & Byers, L. (2016). An investigation of the impact of building orientation on energy consumption in a domestic building using emerging BIM (Building Information Modelling). *Energy*, *97*, 517-527.

Açıl, Ş. (2022). *Sustainable building design with building information management technology* (Publication Number 713216) [Master's Thesis, Fırat University]. Elazığ, Turkey.

Atta, I., Bakhoum, E. S., & Marzouk, M. M. (2021). Digitizing material passport for sustainable construction projects using BIM. *Journal of Building Engineering*, *43,* 103233.

Basbagill, J., Flager, F., Lepech, M., & Fischer, M. (2013). Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts. *Building and Environment*, *60*, 81-92.

Bynum, P., Issa, R. R., & Olbina, S. (2013). Building information modeling in support of sustainable design and construction. *Journal of Construction Engineering and Management*, *139*(1), 24-34.

Carvalho, J. P., Bragança, L., & Mateus, R. (2019). Optimising building sustainability assessment using BIM. *Automation in Construction*, *102*, 170-182.

Cavalliere, C., Habert, G., Dell'Osso, G. R., & Hollberg, A. (2019). Continuous BIM-based assessment of embodied environmental impacts throughout the design process. *Journal of Cleaner Production*, *211*, 941-952.

Cheng, J. C., & Ma, L. Y. (2013). A BIM-based system for demolition and renovation waste estimation and planning. *Waste Management*, *33*(6), 1539-1551.

Figueiredo, K., Pierott, R., Hammad, A. W., & Haddad, A. (2021). Sustainable material choice for construction projects: A life cycle sustainability assessment framework based on BIM and Fuzzy-AHP. *Building and Environment*, *196*, 107805.

Gülaçmaz, Ö. (2021). *An energy efficient approach improvement in an existing educational structure* (Publication Number 671565) [Msc, Tokat Gaziosmanpaşa University]. Tokat.

Ham, Y., & Golparvar-Fard, M. (2015). Mapping actual thermal properties to building elements in gbXML-based BIM for reliable building energy performance modeling. *Automation in Construction*, *49*, 214-224.

Harris, J. M. (2000). Basic principles of sustainable development. *Dimensions of Sustainable Development*, *1*, 21-40.

Harvey, L. D. (2012). *A handbook on low-energy buildings and district-energy systems: Fundamentals, techniques and examples*. Routledge.

Ilhan, B., & Yaman, H. (2016). Green building assessment tool (GBAT) for integrated BIM-based design decisions. *Automation in Construction, 70*, 26-37.

Jalaei, F., & Jrade, A. (2015). Integrating building information modeling (BIM) and LEED system at the conceptual design stage of sustainable buildings. *Sustainable Cities and Society, 18,* 95-107.

Jrade, A., & Jalaei, F. (2013). Integrating building information modelling with sustainability to design building projects at the conceptual stage. Build Simul, *6*(4), 429–444.

Kaewunruen, S., Rungskunroch, P., & Welsh, J. (2018). A digital-twin evaluation of net zero energy building for existing buildings. *Sustainability, 11*(1), 159.

Liu, S., Meng, X., & Tam, C. (2015). Building information modeling based building design optimization for sustainability. *Energy and Buildings, 105*, 139-153.

Marzouk, M., Azab, S., & Metawie, M. (2018). BIM-based approach for optimizing life cycle costs of sustainable buildings. *Journal of Cleaner Production*, *188*, 217-226.

Mersal, A. (2016). Sustainable urban futures: Environmental planning for sustainable urban development. *Procedia Environmental Sciences, 34*, 49-61.

Najjar, M., Figueiredo, K., Palumbo, M., & Haddad, A. (2017). Integration of BIM and LCA: Evaluating the environmental impacts of building materials at an early stage of designing a typical office building. *Journal of Building Engineering*, *14*, 115-126.

Olawumi, T. O., & Chan, D. W. (2018). A scientometric review of global research on sustainability and sustainable development. *Journal of Cleaner Production*, *183*, 231-250.

Olawumi, T. O., Chan, D. W., Wong, J. K., & Chan, A. P. (2018). Barriers to the integration of BIM and sustainability practices in construction projects: A delphi survey of international experts. *Journal of Building Engineering, 20*, 60-71.

Röck, M., Hollberg, A., Habert, G., & Passer, A. (2018). LCA and BIM: Visualization of environmental potentials in building construction at early design stages. *Building and Environment*, *140*, 153-161.

Shadram, F., Johansson, T. D., Lu, W., Schade, J., & Olofsson, T. (2016). An integrated BIM-based framework for minimizing embodied energy during building design. *Energy and Buildings*, *128*, 592-604.

Wong, J. K. W., & Zhou, J. (2015). Enhancing environmental sustainability over building life cycles through green BIM: A review. *Automation in Construction*, *57*, 156-165.

Wu, W., & Issa, R. R. (2015). BIM execution planning in green building projects: LEED as a use case. *Journal of Management in Engineering*, *31*(1), A4014007.

Yang, X., Hu, M., Wu, J., & Zhao, B. (2018). Building-information-modeling enabled life cycle assessment, a case study on carbon footprint accounting for a residential building in China. *Journal of Cleaner Production*, *183*, 729-743.

Generative AI Research Fields in the AEC-FM Industry

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Abstract

This research paper presents a comprehensive scientometric analysis and mapping of the existing literature on Generative AI research fields in the Architecture, Engineering, Construction and Facility Management (AEC-FM) industry. It begins with an overview of Generative AI, emphasizing its ability and then discusses the future potentials of Generative AI applications in the industry. The study employs a tool which uses natural language processing and text mining techniques to analyse the bibliometric data. Through co-occurrence analysis, the research delineates the intellectual structure and evolution of Generative AI use in construction industry. The key fields that have shaped the research area are highlighted as predictive risk management, LLM integration, automated processes, optimized design, and learning systems integration. Furthermore, the study reveals challenges, opportunities, and future prospects according to current research pattern, Finally, it discusses the future potential of Generative AI to significantly transform the AEC-FM industry.

Keywords: *Automation, generative AI, generative design, LLM, predictive management, the construction industry.*

Introduction

The architectural, engineering, construction, and facility management (AEC-FM) industry has traditionally been characterized by manual processes, high physical labour requirements, and relatively slow adoption of new technologies compared to other industries. However, the competitively changing conditions with the introduction of advanced technologies, particularly AI, which is poised to fundamentally transform how projects are planned, designed, executed, and managed. Generative Artificial Intelligence (Generative AI), a transformative technology within artificial intelligence, is adept at creating realistic and diverse content such as text, images, and audio from substantial datasets derived from digital and non-digital sources. Historically reliant on rule-based and heuristic methods, such as genetic algorithms and simulated annealing (Zhang et al., 2022). The field has seen significant evolution due to the increasing availability of big data and advancements in computational power and hardware. This evolution has spurred the adoption of deep learning technologies, increasingly focusing on complex output requirements through structures like the attention mechanism. This mechanism has particularly enhanced the model's ability to manage long-range dependencies crucial in handling complex data types like language and imagery, where elements at the start and end of a sequence are interdependent. The introduction of transformer models has further refined this capability by utilizing weighted relationships between elements during the generation process, allowing for more nuanced and contextually aware outputs. These advancements facilitate multifaceted applications, such as optimizing building schedules while simultaneously testing sustainability performances, and are continuously improved through iterative refinement by leading tech companies. This ongoing development cycle enhances the models' accuracy, coherence, and overall output quality, marking significant progress in the field of Generative AI.

Research Background

Generative AI, a subset of artificial intelligence focused on creating new content and solutions, has begun to immerse in the AEC-FM industry as in others. Unlike traditional AI, which primarily analyzes data, Generative AI can produce new data, predict outcomes, and optimize processes autonomously. The Generative AI applications can be realized through text-to-text models (ChatGPT3 and 4, Gemini Pro, LaMDA, PEER, Galactica, Codex, Claude, Jurassic), text-to-image models (DALL-E2, Parti, IMAGEN, Craiyon), text-to-video/3D models (Imagen, StyleGAN, Phenaki, Magic3D, CogVideo, Lumiere), text-to-task models (Bard, GPT-4, LaMDA, Jarvis), image-to-text models (GPT 4, Gemini Pro), image-to-image models (Pix2Pix), image-to-video models (Stable Video, Diffusion), video-to-text models (VideoCoCa), video-to-image models(there is no any model), and video-to-video models (Lumiere, Gen-2). The potential use areas of these models in the AEC-FM activities are summarized below.

In the design and planning stage, Generative AI can automatically generate multiple design variations based on specified criteria such as dimensions, budget constraints, and aesthetic preferences. This not only speeds up the design process but also offers innovative solutions that might not have been considered. AI-driven tools integrate with BIM models to enhance the design's feasibility by assessing constructability issues early in the design phase. AI algorithms are capable of optimizing the scheduling and allocation of resources, predicting potential delays, and suggesting corrective actions. This helps in reducing downtime and improving the efficiency of the construction process. Furthermore, Generative AI can play a significant role in logistics management, optimizing material procurement and delivery schedules to ensure timely project execution. AI-driven systems can predict risk scenarios and suggest mitigation strategies, improving worker safety. Additionally, these systems ensure that designs comply with current building codes and regulations, which are automatically updated into the AI's learning database.

Generative AI holds the promise of transforming the Architecture, Engineering, Construction, and Facility Management (AEC-FM) industry by enhancing design, construction, and management processes. This transformation could lead to the creation of more efficient, sustainable, and innovative environments. The progression of this technology depends on ongoing advances in AI research, the growing availability of data, and improvements in computational power. These factors will likely play a critical role in bringing the potential of Generative AI to improve the AEC-FM activities in the near future. The purpose of Generative AI in the AEC-FM industry activities can be listed as content generation, data augmentation, personalization, simulation and modeling, and creative assistance. The potential use cases of Generative AI in the AEC-FM industry may be design exploration, 3D model generation, automatic workflow generation, data extraction from models, team management, interior design, landscape design, in-building routing, design optimization, structural analysis, layout orientation alternatives, energy efficient configuration, cost effectiveness, sustainable design, sequencing, scheduling, resource allocation, predictive maintenance, logistics planning, and data driven decision making. The research questions about the Generative AI applications in the AEC-FM industry are listed below:

> RQ1: How is the current state of the of Generative AI research in the AEC-FM industry?
> RQ2: What are the challenges in Generative AI applications in the AEC-FM industry?
> RQ3: What are the opportunities in Generative AI applications in the AEC-FM industry?
> RQ4: What are the future prospects in Generative AI applications in the AEC-FM industry?

Methodology

Scientometric analysis and mapping which allows to empirically analyse the related bibliometric data. Bibliometric search of publications was performed in Scopus, one of the main search engines for academic research outputs. The Scopus database covers more journals and more publications than other sources (Ozturk, 2020; 2021). Scopus uses Boolean syntax for getting consolidated and relevant results. The keyword co-occurrence analysis was employed to identify the research fields. Scientometric mapping is a part of a scientometric analysis that evaluates research tendency and display a research domain's dynamic and structural aspects (Xu et al., 2018; Cobo et al., 2011). VOSviewer is a tool that is used for visualizing large networks via natural language processing algorithms and text mining techniques (Hosseini et al., 2018). The keywords were clustered by VOS clustering technique and unique clusters color-coded in Figures 1 and listed in Table 1 alongside their constituent keywords. Higher strength value shows a stronger *link*. *The number of links* between a keyword and other keywords represents the relatedness between the keywords. *Total link strength* demonstrates the strength of the relationship between keywords. Average publication year of the papers in which a keyword occurs displays the chronology of a keyword's appearance in the related literature. The more recent the average year published, the newer the keyword is and so is the research subject.

Findings and Discussion

The average publication year data shows that the applications in the AEC-FM industry are in a very immature state (Table 1). However, it is obvious that the AEC-FM industry is experiencing a transformative shift through the integration of Generative AI, which revolutionizes key aspects such as design optimization, progress monitoring, and learning systems integrated immersive environments. Deep learning and machine learning algorithms are used to redefine industry standards and activities via enhancing Generative AI. This underscores the potent impact of AI in modernizing and streamlining construction practices.

Generative AI significantly *Predictive Risk Management* (Figure 1 – Cluster 1) by improving accident prevention, hazard recognition, and occupational safety. It utilizes predictive modeling and real-time data analysis from sensors and cameras to foresee and mitigate potential safety hazards, optimizing safety protocols and project management processes. This AI-driven approach not only predicts risky scenarios to prevent accidents but also ensures efficient resource allocation and scheduling to maintain safety standards. Generative AI facilitates a safer, more efficient construction environment, directly aligning occupational safety with enhanced project management strategies by integrating these capabilities.

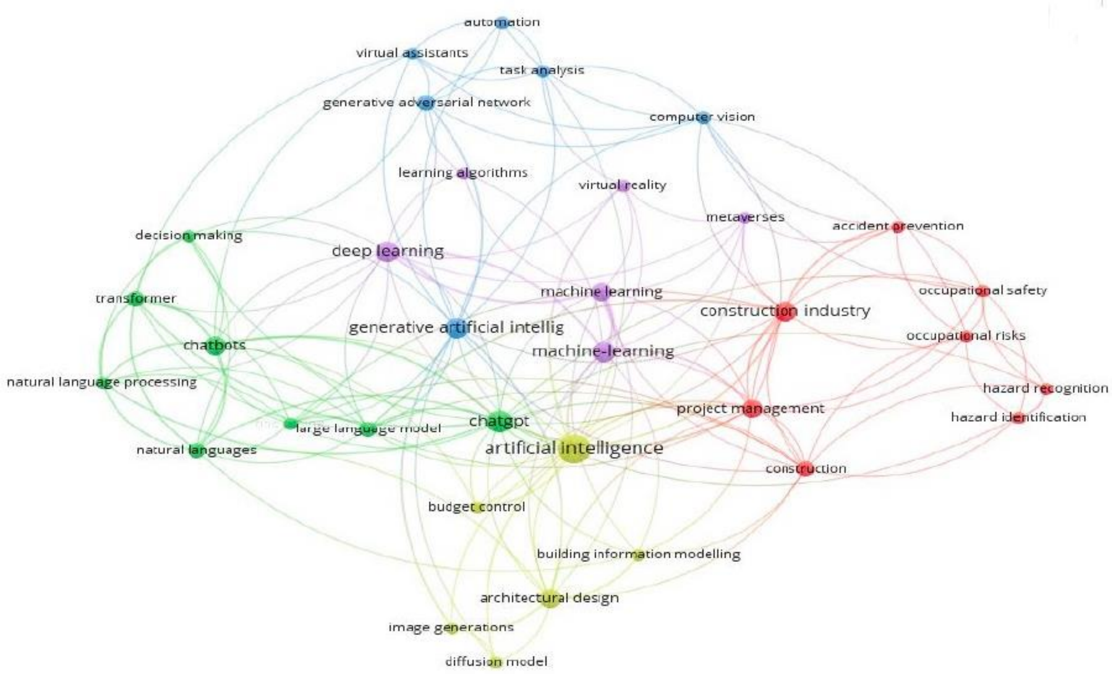

Figure 1: The mapping of the Generative AI research fields (colour distinction) and respective keywords (nodes) in the AEC-FM industry related literature.

LLM-supported Generative AI (Figure 1 – Cluster 2), such as ChatGPT, enhances decision-making through advanced Natural Language Processing (NLP) and transformer models. These large language models interpret and generate natural languages, facilitating fine-tuning to specific industry needs. Stakeholders can interact with AI in conversational formats, receiving instant data-driven information share and decision support by leveraging chatbots. This capability enables rapid, informed decision-making across various construction scenarios. The integration of such technologies ensures that complex data is accessible and actionable, significantly optimizing planning, execution, and management processes in construction projects.

Automated Construction Progress Monitoring (Figure 1 – Cluster 3) uses Generative Artificial Intelligence and mostly Generative Adversarial Networks to enhance the accuracy and efficiency of tracking project advancements. These AI systems analyze visual data from the site, facilitating detailed task analysis and automation of progress reporting by leveraging computer vision. This technology enables virtual assistants to provide real-time updates and insights, reducing manual oversight and increasing project management efficiency. Through automation, these advanced AI tools not only streamline the monitoring process but also ensure that construction schedules are adhered to, thereby optimizing operational workflows and resource allocation.

Generative Design for Design Optimization (Figure 1 – Cluster 4) employs Generative AI, including diffusion models for image generation, to revolutionize architectural design and optimization. This AI-driven approach integrates with Building Information Modeling (BIM) to simulate countless design variations, aligning with specific criteria like budget control and spatial requirements. These systems generate high-quality images and models that propose innovative and efficient solutions, optimizing the use of materials and space by leveraging artificial intelligence. This not only enhances the aesthetic and functional aspects of a building but also ensures that projects adhere closely to predetermined financial constraints, energy efficiency, and regulatory requirements.

Learning Systems Within Immersive Environments (Figure 1 – Cluster 5) leverage Generative AI, deep learning, and machine-learning algorithms to enhance training and operational efficiency. These systems, embedded in virtual reality (VR) platforms or metaverses, simulate realistic construction scenarios where users can interact and learn in a controlled, yet lifelike setting. These AI-driven environments adapt and respond to user inputs using advanced learning algorithms, continuously improving the training modules. By incorporating such immersive, responsive learning experiences, construction professionals can gain practical insights and improve their skills in a safe, virtual space, significantly reducing on-site errors and enhancing overall project efficiency.

Table 1. Generative AI research fields and respective keywords in the AEC-FM industry.

	Link	Total Link Strength	Occurrence Frequency	Average Publication Year
Cluster 1: Predictive Risk Management (red-coded)				
Accident prevention	6	7	2	2024.00
Construction process	13	13	3	2024.00
Hazard recognition	5	6	2	2023.50
Occupational risk	8	8	2	2024.00
Occupational safety	8	8	2	2023.50
Project management	14	18	4	2024.00
Cluster 2: LLM supported Generative AI for Decision Making (green-coded)				
Chatbots	11	17	4	2023.25
Chatgpt	20	28	6	2023.50
Decision making	8	8	2	2023.50
Fine tuning	10	11	2	2023.50
Large language model	12	15	3	2023.67
Natural language processing	8	12	2	2023.00
Natural languages	10	14	3	2023.33
Transformer	9	14	3	2023.00
Cluster 3: Automated Construction Progress Monitoring (blue-coded)				
Automation	5	5	2	2023.00
Computer vision	10	10	2	2023.50
Generative adversarial networks	8	9	3	2023.33
Generative artificial intelligence	15	18	5	2023.60
Task analysis	7	7	2	2023.00
Virtual assistants	7	7	2	2023.00
Cluster 4: Generative design for design optimization (yellow-coded)				

Architectural design	11	14	4	2023.75
Artificial intelligence	16	23	10	2023.50
Budget control	5	6	2	2024.00
Building information modelling	7	8	2	2024.00
Diffusion model	4	5	2	2023.50
Image generation	4	6	2	2023.50
Cluster 5: Learning Systems within Immersive Environment (purple-coded)				
Deep learning	16	20	5	2023.40
Learning algorithms	4	4	2	2023.50
Machine learning	12	19	5	2023.60
Metaverses	7	7	2	2023.50
Virtual reality	6	7	2	2023.00

Challenges
The challenges continue to emerge with the increasing number of Generative AI application in the AEC-FM industry. The extent of challenges can be classified under five groups (adopted from Taiwo et al., 2024) as; *Technological challenges* (model instability, model training, computing power, accuracy, reliability, explainability, data labelling and annotation, interoperability); *Domain-specific challenges* (domain knowledge, data type, lack of datasets, standards integration, unclear standards and rules, liability, unclear quality parameters, old protocols); *Adoption challenges* (resistance to change, lack of skills and expertise, investment cost, immature organizational and technological infrastructure, old version workflows); *Regulatory challenges* (risk management criteria, quality protocols, safety protocols, privacy requirements, redefined standards and procedures, legal liability); *Ethical challenges* (data privacy, data security, potential misuse).

These challenges highlight the complexity and unique considerations that need to be addressed when implementing Generative AI in construction activities. Overcoming these obstacles will be crucial for realizing the full potential of AI technologies in transforming the AEC-FM industry.

Opportunities
Incorporating Generative AI with immersive technologies enhances the visualization and simulation of designs before construction, improving stakeholder understanding and decision-making through improving design communication. For construction planning, the technology can automate the creation of optimized schedules and resource allocation plans, reducing project timelines and costs which in turn positively effects the project management performance. Additionally, Generative AI supports autonomous monitoring and control by analyzing data from image and video recording sources and sensors to detect anomalies and safety risks on construction sites, thereby improving project management, safety, and quality control. Generative AI also contributes to lifecycle management and sustainability by optimizing building operations and maintenance schedules based on real-time and historical data, which promotes energy efficiency and sustainability. Moreover, Generative AI supported building models that can continuously learn from the data acquired throughout the building lifecycle may improve predictive action ability of the Digital Twins.

Most research in the AEC-FM industry uses Generative Adversarial Networks (GANs) due to their ability to generate realistic data with minimal need for large datasets. Despite challenges such as training stability and hyperparameter sensitivity, other models like Deep Convolutional Generative Adversarial Network (DCGAN), Variational Autoencoder (VAE), Conditional

Variational Autoencoder (CVAE), StyleGAN, CycleGAN, DeepArt, Pix2Pix, Autoencoder Variational Bayes (VAE), Generative Pre-trained Transformer (GPT) also have potential for enhancing AEC-FM activities. As Generative AI evolves, it is expected to introduce more advanced automation, sustainability, and resilience in the industry.

Future Prospects

Generative AI is poised to significantly impact the AEC-FM industry by enhancing various processes across the industry. The technology facilitates intelligent design assistance, enabling the generation of optimized design proposals that consider multiple factors such as client requirements, site constraints, and historical data. Developing AI models that can accurately extract detailed project information from various construction documents and BIM models. Techniques to automatically generate feasible building designs based on requirements. Automatic generation of Digital Twins may lead an augment in lifecycle performance of the buildings and infrastructures. These methodologic advancements help architects and engineers make informed decisions, leading to more innovative and efficient solutions for industry needs. At the urban planning level, Generative AI can produce alternative urban layouts and transportation systems, improving sustainability and quality of life. Buildings or infrastructures can communicate through AI assistants (chatbots) with stakeholders about project details, requirements, operation details, situational information, safety, etc. during construction and facility management of the entity in order to speed up the decision making. Automatic generation and comparison of the as-designed and as-built version to monitor construction progress and evaluate the results for predictive scheduling using visual site data. Enhancing and effectively managing safety and quality via real-time visual site data engineering.

While there are some studies on the usage of generative AI for construction-related work, there is a need for more systematic and comprehensive literature that assess the impact of Generative AI use in the AEC-FM industry (Ozturk and Soygazi, 2024; Ghimire et al., 2024; Buhamdan et al., 2021). Practical and actionable guidance on implementing and deploying Generative AI solutions in the AEC-FM industry activities is essential. Generative AI holds significant promise for transforming the industry by addressing productivity challenges and driving innovation. However, overcoming domain-specific, technological, adoption, regulatory and ethical challenges is crucial for the successful adoption and implementation of Generative AI applications in construction activities for improved productivity, cost savings, communication, and project management. Addressing these challenges and seizing opportunities can lead to transformative advancements in the industry.

Limitations

The limitations of this paper include only the perspective on Generative AI applications related to AEC-FM activities. This focused approach results in missing the innovative implementations of other industries. In particular, the future research can consider the use cases of Generative AI in more technologically adopted industries to depict further opportunities for the AEC-FM industry. There is a limited number of papers on Generative AI in the AEC-FM literature. As the technology improves rapidly, the literature is growing exponentially, leading to delayed diagnosis of challenges and outdated commentary. There is a need for collaborating computer scientists to understand how to overcome the technological challenges and make insightful contributions to the literature.

Conclusions

The paper explores the research field of Generative AI applications in the Architecture, Engineering, Construction, and Facility Management (AEC-FM) industry. The study provides a comprehensive analysis of existing literature, identifies key research themes, and suggests promising research directions for the future while referencing limitations. The paper also emphasizes the importance of addressing domain-specific, technological, adoption, regulatory, and ethical challenges to ensure the successful implementation of Generative AI solutions in construction activities, while mentioning the transformative potential of Generative AI in enhancing productivity, driving innovation, and improving communication and project management in the AEC-FM industry. Generative AI applications can be benefit with its contribution to BIM, energy efficiency and sustainability, advanced materials, structural engineering, architecture, construction automation and robotics, smart cities, resilient infrastructure, construction management, predictive and proactive project management, risk management, safety, quality management, and supply chain management. Prospective studies should consider further benchmarking other industry experiences, developing adoption strategies, and improvements in overcoming technological challenges.

References

BuHamdan, S., Alwisy, A., & Bouferguene, A. (2021). Generative systems in the architecture, engineering and construction industry: A systematic review and analysis. *International Journal of Architectural Computing*, *19*(3), 226-249.

Ghimire, P., Kim, K., & Acharya, M. (2024). Opportunities and Challenges of Generative AI in Construction Industry: Focusing on Adoption of Text-Based Models. *Buildings*, *14*(1), 220.

Ozturk, G. B. (2020). Interoperability in building information modeling for AECO/FM industry. *Automation in Construction*, *113*, 103122.

Ozturk, G. B. (2021). Digital twin research in the AECO-FM industry. *Journal of Building Engineering*, *40*, 102730.

Ozturk, G. B., & Soygazi, F. (2024). Generative AI Use in the Construction Industry. In *Applications of Generative AI* (pp. 161-187). Cham: Springer International Publishing.

Xu, Y., Zeng, J., Chen, W., Jin, R., Li, B., & Pan, Z. (2018). A holistic review of cement composites reinforced with graphene oxide. *Construction and Building Materials*, *171*, 291-302.

Cobo, M. J., López-Herrera, A. G., Herrera-Viedma, E., & Herrera, F. (2011). An approach for detecting, quantifying, and visualizing the evolution of a research field: A practical application to the Fuzzy Sets Theory field. *Journal of informetrics*, *5*(1), 146-166.

Hosseini, M. R., Martek, I., Zavadskas, E. K., Aibinu, A. A., Arashpour, M., & Chileshe, N. (2018). Critical evaluation of off-site construction research: A Scientometric analysis. *Automation in construction*, *87*, 235-247.

Taiwo, R., Bello, I. T., Abdulai, S. F., Yussif, A. M., Salami, B. A., Saka, A., & Zayed, T. (2024). Generative AI in the Construction Industry: A State-of-the-art Analysis. *arXiv preprint arXiv:2402.09939*.

A Grey Model for Evaluating the Resilience of Construction Project Teams

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Abstract

The concept of resilience has been receiving overwhelming interest from scholars for quite some time. It has also been occupying a central position on the agenda of built environment scholars. A closer review of previous research studies in the built environment literature reveals that the concept of resilience has been predominantly applied to the objects of the built environment (i.e., buildings, infrastructures, cities), while the resilience of subjects within the built environment (i.e., individuals, teams, organizations) has remained an underexplored research area. The research presented herein explores the resilience of subjects within the built environment. It proposes a conceptual model to evaluate the resilience of construction project teams. Project team resilience is commonly conceptualized as either a (i) capacity, (ii) process, or (iii) outcome. The proposed model adopts an integrated approach to explore and develops a linguistic model to evaluate the resilience of project teams. A hypothetical case is proposed to illustrate the application and utility of the proposed model.

Keywords: *construction industry, evaluation, linguistic variable, model, project teams, resilience.*

Introduction

Research studies on the literature of the resilience concept in the built environment typically concentrate on objects, such as physical structures. Conversely, studies that prioritize the subjects within the built environment, emphasizing relationships and organizational levels, are relatively scarce. Research studies predominantly focusing on objects typically explore the physical resilience concept at various scales, ranging from buildings to infrastructure, cities, regions, and countries. In contrast, research studies focusing on subjects aim to probe the resilience of social actors such as individuals, teams, and organizations. The dearth of studies focusing on subjects underscores an opportunity to delve into this domain in depth, potentially unveiling novel avenues. Therefore, this study proposes a conceptual model to assess the resilience of project teams within the construction industry.

The concept of resilience is a multidimensional concept that can be explored through the lenses of capacity, process, and outcome concepts. Evaluating the resilience of project teams is a challenging issue for scholars but also for practitioners, mainly due to the uncertainty involved in this process. The research presented herein addresses this challenge by developing an evaluation model based on Grey Systems Theory. A hypothetical case study is presented to demonstrate the applicability and utility of the proposed model.

The Concept of Resilience

The concept of resilience, defined as the ability to resist challenges, has been extensively explored from ancient times to the present day and is currently studied in various disciplines such as social sciences, psychology, and management (Akbaş, 2023). Today, resilience is explored through the lens of adapting to changing conditions, coping with stress, and managing crises. Different disciplines in the literature approach this concept in distinct ways (Hassler & Kohler, 2014). For instance, social systems define it as the ability to withstand external shocks (Adger, 2001); ecological systems describe it as a measure of persistence and the ability to absorb change (Walker et al., 2004); disaster risk management highlights it as the ability of units to mitigate hazards (Bruneau et al., 2003); individual resilience is defined as an individual's ability to adapt to stress and challenges (Alliger et al., 2015); team resilience is emphasized as the capacity of a team to overcome challenges to achieve sustained performance (Alliger et al., 2015), and organizational resilience is the ability to survive in an uncertain environment (Hatton et al., 2012).

In the context of the built environment, the concept of resilience is often studied due to the complexity and uncertainty inherent in project processes. Project-level resilience focuses on developing strategies for adapting to, reducing, and managing uncertainty, as well as being prepared for the risks, complexity, and uncertainty associated with projects. This contributes to enhancing the sustainability and success of projects. On the other hand, resilience within the context of project stakeholders and organizations, focusing on subjects of the built environment, is examined through the ability of stakeholders and organizations to generate efficient and effective solutions to challenges. This is attributed to the variability of stakeholders, the abundance of resources, and the requirement for multidisciplinary expertise in diverse working areas.

In the built environment literature, research studies predominantly focus on resilience to disasters. Chmutina and Rose (2018) study disaster risk reduction (DRR) measures. Akbaş (2023) emphasizes the importance of developing strategies in the areas of risk management, sustainability, planning, infrastructure, social factors, and local governance for disaster-resistant cities. Bingöl et al. (2020) focus on earthquake-resistant architectural design. Bosher et al. (2007) discuss 'built-in' resilience against natural disasters by indicating required principles such as the contribution of new stakeholders, a multidisciplinary view, economical and legal structure, etc. Wedawatta et al. (2011) investigate the resilience of small and medium-sized enterprises (SMEs) in the construction sector in the United Kingdom against extreme weather conditions.

Research studies that focus on the resilience of subjects in the built environment adopt various unit levels of analysis such as organizational, team, and individual levels. Hassler and Kohler (2014) emphasize the development and integration of heuristics in resilience assessment, supported by organizational-level policies. Kruth et al. (2019) point out that risk management-focused studies do not address stressors, leading to several barriers such as indeterminate analytical meaning, event and performance uncertainty, immature regulatory standards setting, and untested enterprise economics. Sapeciay et al. (2019) focus on several key indicators for construction organizational resilience assessment, such as leadership, staff engagement, decision-making, situation awareness, planning strategies, internal resources, proactive posture, effective partnership, innovation and creativity, unity of purpose, stress testing plan, breaking silos, and leveraging knowledge. Anderies (2014) discusses the design principles for resilience by emphasizing the integration of nature and the human-built environment and the required design principles. Wilkinson (2016) emphasizes the required strategies for the construction sector, such as government position, education and research, collaboration, adapting to changes, etc., to increase resilience toward risks, hazards, and uncertainties. Wang and Zhang (2023) indicate the importance of resources that dominate proactive organizational resilience in construction, besides institutional factors, and propose a basis for organizational resilience that focuses on crisis preparedness and recovery efforts to respond to unexpected challenges. For the team-level resilience studies, Turner et al. (2021) focus on team resilience and explore how women cope with challenging working environments in the construction sector. Hartwig et al. (2020) develop a multilevel conceptual model of team resilience, and Grimm et al. (2023) study the dynamic measurement of team resilience. Finally, for the individual-level resilience studies, Chen et al. (2017) investigate the relationship between individual resilience and personal relationships in the workplace among construction workers. As observed, while organizational resilience is frequently studied in research related to construction, team and individual resilience have been relatively underexplored in the literature. In this study, team resilience will be discussed and assessed in the practice of the built environment.

Team resilience has typically been conceptualized over a process, ability, belief, or capacity in the literature, but it is defined as the team members' ability to overcome adversities and challenges that affect the targeted success (Stoverink et al., 2020). In general terms, team resilience can be defined as the ability to withstand and recover from challenges while maintaining its cohesion and performance levels (Alliger et al., 2015). Resilient teams have cohesive strategies such as minimizing, managing, and repairing challenges to ensure their long-term sustainability (Alliger et al., 2015). This resilience is not only about overcoming challenges but also about learning from them and growing as a result (Stoverink et al., 2020). Teams face challenges and difficulties in achieving their goals; in here, the term "irresilience" can be used to signify the inability to demonstrate the expected or desired level of resilience or resistance due to weaknesses, indicating a collapse in the face of difficulties. Team resilience is a dynamic process including resistance, bounce back, and recovery interactions among team members and their environments that reflect the team's response to their performance (Gucciardi et al., 2018). In conclusion, team resilience is a multifaceted concept crucial for teams to navigate successfully in complex work environments (Stoverink et al., 2020). It requires a shared commitment to managing challenges collectively, adapting to changing circumstances, and fostering a resilient culture that supports continuous growth and effectiveness (Alliger et al., 2015).

Several models have been proposed to evaluate the resilience of social actors. Hartwig et al. (2020) propose a conceptual model that integrates individual-level factors, such as team members' relevant knowledge, abilities, and skills. The proposed model includes three factors: input, mediator, and outcome. Input encompasses team and individual-level factors such as transformational leadership, relationships, culture at the team level, and communication skills, expertise, resilience, and team orientation at the individual level. The mediator comprises team states such as cohesion, collective efficacy, psychological safety, team identity, mental models, and trust, as well as team resilient behaviours such as communication, cooperation, coordination, and behaviours aimed at minimizing, managing, and mending challenges. Finally, the outcome encompasses team outcomes such as performance, health, and team functioning, along with the team's emergent resilience state (Hartwig et al., 2020). Grimm et al. (2023) conducted two experiments on Human-Autonomy Teams (HATs) operating a simulated Remotely Piloted Aircraft System (RPAS), correlating dynamical measures of team resilience with team performance measures. Grimm et al.'s (2023) findings contribute insights to team collaboration measurement, monitoring, and evaluation strategies. Nemeth et al. (2011) propose Cognitive Systems Engineering (CSE) methods to comprehend and enhance the concept of resilience. Harvey et al. (2019) propose an approach for the construction sector, highlighting the project-based nature, temporary workforce, extensive use of outsourced labour, and financial pressures as distinctive features. They situated this within the context of High Reliability Organizing (HRO) and Resilience Engineering (RE) as key concepts in safety management. Yang and Cheng (2020) investigate the impact of organizational resilience on the success of construction projects through large-scale construction examples. Their study emphasizes the need to enhance organizational resilience for project success in the face of environmental uncertainty, social events, and increasing challenges. They utilize the crisp-set Qualitative Comparative Analysis (csQCA) method on a literature review and case studies. The research identifies timely situation monitoring, flexible organizational structure, cohesive organizational culture, and the participation of multiple subjects as key factors influencing the success of construction projects. Gucciardi et al. (2018) present a conceptual model for individual, team, and organizational levels of work team resilience, conceptualizing it as a multilevel emergent construct. The model includes the inputs (human capital resources, leadership, norms, mental models), processes (planning, reflection, and coordination), and outcomes (trajectories of functioning and a shared belief) of team resilience emergence, offering nine key propositions. Stoverink et al. (2020) present a theoretical model of work team resilience, emphasizing setbacks as disruptions in team processes and detailing the "bouncing back" process wherein teams, facing setbacks, strategically invest in critical resources to return to or exceed prior performance levels. They highlight the interdependence of team member activities and theorize the strengthening of resilience over time through experiences. Wehbe et al. (2016) analyse safety management and communication networks in the construction industry using methods such as Social Network Analysis (SNA) and agent-based modelling. Parvin and Shaw (2011) study on climate disaster resilience and evaluated the city over the Climate Disaster Resilience Index and the different dimensions of the city, especially its physical, social, economic, institutional, and natural dimensions using SWOT analysis. Emmanuel and Krüger (2012) investigate urban heat island and its impact on climate change, considering resilience to local climate variations, urban growth, historical trend analysis, and pairwise comparisons. Bingöl et al. (2020) explore earthquake-resistant architectural design using artificial intelligence, deep learning, and image processing methods to detect irregularities in structural systems for earthquake resilience. Peñaloza et al. (2020) evaluated the contribution of Safety Performance Measurement Systems (SPMS) in monitoring and understanding the sources of complexity and resilience in construction projects. They utilized the Technical, Organizational, and Environmental (TOE) framework for complexity and the Resilience Assessment Grid (RAG) for resilience. Their study resulted in the identification of improvement opportunities for existing SPMS and the emergence of guidelines and a model explaining the connections between key constructs.

The research constructs emphasized by the above-discussed models focusing on construction resilience are summarized in the table below:

Table 1. Research constructs used in construction resilience related studies.

Source	Research constructs	Focus
Stoverink et al. (2020)	• Team potency • Team mental model of teamwork • Team capacity to improvise • Team psychological safety	• Subject of built environment (SBE)
Yang and Cheng (2020)	• Situation monitoring (situation awareness, digital application) • Organizational structure (innovation and creativity, resource redundancy, planning strategies) • Organizational culture (effective partnerships, information disclosure, organizational cohesion) • Participants (multiple subjects, public participation)	• SBE
Gucciardi et al. (2018)	• Inputs (human capital resources, leadership, norms, mental models) • Processes (planning, reflection, and coordination) • Outcomes (trajectories of functioning and a shared belief)	• SBE
Wehbe et al. (2016)	• network characteristics and communication pattern • actual safety performance data	• Object of built environment (OBE)
Parvin and Shaw (2011)	• Climate Disaster Resilience Index (CDRI) • dimensions (physical, social, economic, institutional and natural	• OBE
Emmanuel, and Krüger (2012)	• Local climate variations • urban growth • historical trend analysis	• OBE
Bingöl et al. 2020	• Earthquake code of Türkiye • Irregular structural systems • Regular structural systems	• OBE
Peñaloza et al. (2020)	• Technical, organizational, environmental sources • Resilience potentials: respond, monitor, learn and anticipate	• OBE

It is clear from Table 1 that subjects of the built environment (i.e., social actors) exhibit a complex and multidimensional structure. Therefore, research on the built environment often requires a variety of research constructs to address the complexity and multidimensionality. On the other hand, objects of built environment (i.e., constructed facilities) can often be more specific and concrete. Consequently, research on objects may entail clearer and more specific research constructs. This situation arises from the fundamental differences between subject and object in research on the built environment. While subject-oriented research may encompass topics such as human behaviour, perception, and preferences, object-oriented research may focus more on elements such as physical properties, design elements, and building materials. In summary, while the number of studies focusing on the subject of the built environment is fewer than studies on its objects, there are more research constructs for subjects due to their complexity and multidimensionality.

This study presents a model that conceptualizes the resilience of project teams in construction projects through processes, capacities, and outcomes. It assesses the resilience of project teams using Grey System Theory.

Linguistic Modelling and Grey System Theory

Linguistic modeling is a discipline employed to comprehend complexity and ambiguity through various language processing methods. These methods analyze the structure, functioning, and use of language (Donc & Xu, 2018). Additionally, systems analysis methods are utilized to address system uncertainties. These methods, such as Fuzzy Logic, Probabilistic Models, Bayesian Networks, Monte Carlo Simulation, Interval Analysis, Neural Networks, and Grey System Theory, can be integrated with linguistic modeling to model and analyze intricate language aspects (Ayyup & Klir, 2006).

Grey System Theory is a theory specifically devised for system analysis and prediction in situations of uncertainty and limited data (Liu et al., 2011). Unlike other system analysis methods that involve uncertainty, Grey System Theory possesses the capability to make meaningful predictions and adapt to dynamic changes. For these reasons, this study will employ the Grey System Theory approach in the proposed model to assess team resilience, which encompasses dynamic and complex factors.

Grey System Theory, proposed by Deng, serves as a tool to seek solutions based on partially known and uncertain information. Grey relational analysis, a method within Grey System Theory, examines relationships between discrete interval data. The principles of Grey System Theory are compatible with many business research methods, with numerous studies conducted in recent years (Çakir, 2008). The concept of grey systems derives its name from the color grey, symbolizing partially known and partially unknown information. In this context, it provides a framework for analyzing systems across various fields such as social, economic, agricultural, industrial, ecological, or biological. Insufficient information may manifest in various forms, including system components or variables, organization or system limits, and motion behavior (Liu et al., 2011).

In Grey systems, it is crucial that some information is revealed while some remains hidden. These systems are categorized into dark systems (completely unknown), white systems (fully understood), and Grey systems (partially disclosed and partially undisclosed). Unlike black systems, which do not provide a definite outcome, and white systems, which present a singular solution, grey systems may yield multiple solutions (Liu et al., 2011).

Three grey-based methods have been studied in the literature, namely the "LI," "GR," and "NG" methods (Jadidi et al., 2009). The LI method is employed to rank alternatives based on grey probability rank. GR analysis aims to minimize the maximum distance from the ideal reference alternative. The NG method selects the most desirable alternative by calculating the weighted connection between the ideal and negative ideal reference alternatives. While each method entails unique steps, all focus on solving decision-making problems relying on incomplete information (Jadidi et al., 2009).

Grey – Project Team Resilience Evaluation Model

In this study, the Grey-Team Resilience Evaluation (G-PTRE) model is proposed. This model uses linguistic terms to assess team resilience in construction projects. In the light of literature review presented in previous section (Table 3) three main evaluation criteria, namely capacity, process, and outcome, are used in the proposed model. The concept of capacity includes six dimensions: (1) *'team potency'* refers to the team's belief in the ability to successfully solve tasks and overcome crises, (2) '*capacity to improvise'* assesses the team's flexibility and ability to quickly adapt to changing conditions and demands (3) *'psychological safety/trust'* measures how capable team members feel to express themselves emotionally and intellectually and share their ideas freely, (4) *'diversity and inclusion'* consider the contribution of diverse perspectives to team activities, (5) *'resource availability and allocation'* evaluates the amount of available resources and their efficient distribution and (6) *'leadership and communication'* evaluates the effectiveness of team leadership and communication styles in improving collaboration and team effectiveness. The concept of process includes five dimensions: (1) '*monitoring (mental and physical)'* involves using sensors to detect potential crises and react quickly to changing conditions, (2) 'collaboration and coordination/planning' evaluates the team's ability to collectively prepare mechanisms to process projects efficiently and effectively, (3) *'learning and adaptability'* focuses on the team's capacity to learn from past experiences and adapt to new circumstances, (4) *'conflict resolution and decision making'* examine the positive outcomes of effective harmony among team members and (5) 'feedback and performance evaluation' promote team development and goal achievement. The concept of outcome includes five dimensions: (1) *'project success and performance'* measures the successful achievement of project objectives, (2) *'customer satisfaction and stakeholder impact'* measure the success of the team and its capacity to create value for stakeholders, (3) *'culture'* supports the organization's crisis management ability and long-term sustainability by assessing the resilience of the team's culture, (4) *'innovation and creativity results'* evaluate the level of innovation and creativity in the team's results and (5) *'team engagement and satisfaction'* measure the impact of team commitment and motivation.

Table 2. Factors used for assessing team resilience in the literature.

Author(s)	Research Construct	Description
Stoverink et al. (2020)	Team potency	belief of successfully resolving tasks
	Team mental model	members' collective understanding of roles, responsibilities, and each other's skills and preferences, enabling seamless collaboration.
	Team capacity to improvise	ability to creatively adapt to demands by drawing on past experiences and knowledge, requiring both proactive planning and the spontaneous generation of novel ideas.
	Team psychological safety	collective understanding within a team that it is safe to express oneself emotionally and intellectually, share ideas, and propose new concepts without fear of judgment or reprisal.

Yang and Cheng (2020)	Situation monitoring (situation awareness, digital application)	organization's continuous use of sensors to detect potential crises.
	Organizational structure (innovation and creativity, resource redundancy, planning strategies)	formal design of roles and management to regulate work and resources.
	Organizational culture (effective partnerships, information disclosure, organizational cohesion)	shared beliefs, behaviours, and values shaping organizational effectiveness and resilience, divided into indicators like partnerships, information sharing, and cohesion.
	Participants (multiple subjects, public participation)	those involved in activities or projects, such as construction, disaster recovery, or other initiatives.
Gucciardi et al. (2018)	Inputs (human capital resources, leadership, norms, mental models)	existing factors related to individuals, team formation, and the work context that influence interactions within a team.
	Processes (planning, reflection, and coordination)	mechanisms through which inputs are combined and transformed into outcomes, such as coordination among team members.
	Outcomes (trajectories of functioning and a shared belief)	valued results or consequences of team interactions directed towards achieving a common objective, including performance and commitment.

Table 3. Evaluation criteria for team resilience.

C_i		
Capacity (C_1)	Team potency - belief in successfully resolving tasks; team's ability to overcome crises and challenges	
	Capacity to improvise -team's capacity for flexibility and rapid adjustment to changing conditions and demands	
	Psychological safety/Trust - enabling members to freely express themselves emotionally and intellectually and to share ideas	
	Diversity and inclusivity - contribution of various perspectives to the team activities	
	Resource availability and allocation - quantity of available resources and their efficient distribution	
	Leadership and communication - team leadership and communication style that effect collaboration and effectiveness within the team	
Process (C_2)	Monitoring (mental and physical) - utilization of sensors to detect potential crises and ability to rapidly react to changing conditions	
	Collaboration and coordination/planning - ability to prepare mechanisms collectively to process projects efficiently and effectively	
	Learning and Adapting - learning from the past experiences and adopting to the new circumstances	

	Conflict resolution and decision making- affirmative result of effective adaptation among team member
	Feedback and performance evaluation - fostering team development and processes of achieving goals.
Outcome (C_3)	Project success and performance -successful achievement of goals
	Customer satisfaction and stakeholder impact - measure of team's success and value creation capacity
	Culture - a resilient culture, supporting the organization's crisis management ability and long-term sustainability
	Innovation and creativity outcomes - team's level of innovativeness and creativity in outcomes
	Team cohesion and satisfaction - impact team commitment and motivation

The basic operators used for the proposed model are as follows (Çakir, 2008):

1- Grey Summation Rule: It is used to calculate the sum of two grey numbers.

$$\sum_{j=1}^{n} \otimes = \left(\sum_{j=1}^{n} a_{ij}, \sum_{j=1}^{n} b_{ij}\right), \forall i = 1, \dots, n. \quad (1)$$

2- Grey Multiplication Rule: It is used to calculate the product of two grey numbers. Minimum and maximum values are taken from the cross products of grey numbers.

3- Grey Reciprocal Rule: It is used to calculate the inverse of a grey number.

4- Value of grey extent: It is used to make comparison values between objects.
4a- Whitening grey expansion values: It is used to obtain a whitened value for each grey expansion value.
4b- Vector Operators and Normalization: It is used to process grey expansion values into a vector. Normalizing the vector is used to determine the weight of each grey expansion value (Çakir, 2008).

These operators are used to evaluate the relationships between grey numbers and the ability of grey systems to deal with uncertainty (Çakir, 2008). The primary steps of the proposed model are as follows:

1- *Determination of Evaluation Criteria*: It includes determining the criteria (C_i, i=1,…j) affecting team resilience. A concise literature review suggest that three criteria play an important role on the resilience of project team (Table 3).

2- *Definition of Linguistic Variables*: The language variables that will be used to evaluate importance (W_i) and performance rating (R_i) of each evaluation criterion (C_i, i=1,…3) should be determined. These variables allow evaluators team members to express their preferences regarding these factors (C_i, i=1,…3). The linguistic variables used in the proposed model and their Grey number representation values are presented in Table 3.

3- *Constructing the Pairwise Comparison Matrix for Importance Weights (W_i) and Performance Ratings (R_i)*: A pairwise comparison matrices of evaluation criteria (C_i, i=1,…3) are developed (Table 4).

4- *Application of Grey Extent Analysis*: The Grey extent analysis (Çakir, 2008) is performed using the pairwise comparison matrices.

5- *Determination of Priorities*: The Grey priority vectors obtained for each factor are normalized and the priority order of the factors is determined.

6- *Team Assessment*: Priority vectors determine which factors the team should focus on to improve its resilience. This step is used to identify the team's resilience and areas for improvement.
7- *Determining the Results – Resilience Score (RS)*: The action plans to be taken to increase the resilience of the team are determined. These action plans may include strategies to highlight the team's resilience and improve its weaknesses.

Implementation of G-PTRE Model

Project team resilience will be evaluated through a hypothetical numerical example. The pairwise comparison matrices for importance weights (Wi) and performance ratings (Ri) for evaluation criteria (C_i, i=1,..3) are constructed by an expert (i.e., capacity (C_1), process (C_2) and outcome (C3)). The linguistic variables used for measuring the importance weights (W_i) and performance ratings (R_i, i=1,…3) of resilience evaluation criteria are presented in Table 3. Table 4 presents pairwise comparison matrices for importance weights (W_i) and performance ratings (R_i, i=1,…3).

Table 4. Linguistic variables for measuring importance weights (W_i) and performance ratings (R_i).

W_i		R_i		Grey Values	
Very Weak Importance	WVI	Very low	VL	0.33	0.50
Low Importance	LI	Low	L	0.50	1.00
Equal Importance	EI	Moderate	M	1.00	1.00
Strong Importance	SI	High	H	1.00	2.00
Very Strong Importance	VSI	Very High	VH	2.00	3.00

Table 5. Pairwise comparison matrices for importance weights (W_i) and performance ratings (R_i).

W_i				R_i			
	W_1	W_2	W_3		R_1	R_2	R_3
W_1	EI	VSI	EI	R_1	M	VH	L
W_2	WVI	EI	SI	R_2	VL	M	H
W_3	EI	LI	EI	R_3	H	L	M

The pairwise matrices are used to facilitate the grey extent analysis. Table 6 presents the implementation steps of the proposed model – (i.e., Grey summation, value of grey extends, whitenization and normalization of vector).

Table 6. The implementation steps and results of grey extend analysis.

Grey summation for W_i and R_i

$$\sum_{j=1}^{n}\otimes_{ij} = \left(\sum_{j=1}^{n} a_{ij}, \sum_{j=1}^{n} b_{ij}\right), \quad \forall\ i = 1, \ldots, n \qquad (2)$$

	$\sum_{ai}$	$\sum_{bj}$
W_1	3.00	4.00
W_2	2.33	3.50
W_3	2.50	3.00
R_1	3.33	4.50
R_2	2.33	3.50
R_3	2.50	4.00

Grey extent values for W_i and R_i

$$\gamma_i = \sum_{j=1}^{n}\otimes_{ij} \cdot \left(\sum_{i=1}^{n}\sum_{j=1}^{n}\otimes_{ij}\right)^{-1} \qquad (3)$$

	γ_i	γ_j
W_1	0.29	0.51
W_2	0.22	0.45
W_3	0.24	0.38
R_1	0.27	0.55
R_2	0.19	0.43
R_3	0.21	0.49

Whitenizations of the grey extent values

$$p(\gamma_i) = min_{j=1,\ldots,n, j\neq i}\left\{\Pr\left(\left(\gamma_i > \gamma_j\right)\right)\right\} \qquad (4)$$

	$P(\gamma_i)_{min}$
$p(W_1)$	0.74
$p(W_2)$	0.26
$p(W_3)$	0.15
$p(R_1)$	0.70
$p(R_2)$	0.18
$p(R_3)$	0.30

Normalizing Importance Weights (γ_i)and Performance Ratings (r_i)

$$\omega_i = \frac{p(p_{\gamma_i})}{\sum_{i=1}^{n} p_{(\gamma_i)}} \quad \text{(5a) and}$$

$$r_i = \frac{p(p_{\gamma_i})}{\sum_{i=1}^{n} p_{(\gamma_i)}} \quad \text{(5b)}$$

	Normalized Values (ω_i and r_i)
ω_1	0.65
ω_2	0.22
ω_3	0.13
r_1	0.60
r_2	0.15
r_3	0.25

Evaluation Score

$$RS = \sum_{i=1}^{n} \omega_i * r_i \qquad (6)$$

	S_i
C_1	0.39
C_2	0.03
C_3	0.03
Resilience Score (RS)	0.45

The results of the hypothetical case indicate that capacity (C1) carries the highest importance weight (ω3=0.65), while outcome (C3) has the lowest importance weight (ω3=0.13). It is evident from the hypothetical evaluation model results that the process (r_2=0.15) and outcome (r_3=0.25) performances of the project team should be improved to increase the resilience score.

Conclusion

The proposed G-PTRE Model effectively evaluates project team resilience. Its results offer valuable insights to project managers and stakeholders for assessing and enhancing the resilience level of project teams. This model will serve as a valuable tool for researchers, managers, and practitioners interested in project management and team performance in the construction industry. Additionally, the G-PTRE model will aid in identifying action plans and strategies to bolster the resilience of project teams. Testing this model with real data in future studies will contribute significantly to advancements in the field.

References

Adger, W. N. (2000). Social and ecological resilience: are they related? *Progress in Human Geograph*y, *24*(3), 347-364.

Akbaş, İ. (2023). Dirençlilik ve dirençli kent yaklaşımında yeni eğilimler: bibliyometrik bir analiz. *Nevşehir Hacı Bektaş Veli Üniversitesi SBE Dergisi*, *13*(3), 1866-1889.

Alliger, G. M., Cerasoli, C. P., Tannenbaum, S. I., & Vessey, W. B. (2015). Team resilience: how teams flourish under pressure. *Organizational Dynamics*, *44*(3), 176-184.

Ayyub, B. M., & Klir, G. J. (2006). *Uncertainty modeling and analysis in engineering and the sciences*. Chapman and Hall/CRC.

Bingöl, K., Aslı, E. R., Örmecioğlu, H. T., & Arzu, E. R. (2020). Depreme dayanıklı mimari tasarımda yapay zeka uygulamaları: derin öğrenme ve görüntü işleme yöntemi ile düzensiz taşıyıcı sistem tespiti. *Gazi Üniversitesi Mühendislik Mimarlık Fakültesi Dergisi*, *35*(4), 2197-2210.

Bosher, L., & Dainty, A. (2011). Disaster risk reduction and 'built-in'resilience: towards overarching principles for construction practice. *Disasters*, *35*(1), 1-18.

Bosher, L., Dainty, A., Carrillo, P., & Glass, J. (2007). Built-in resilience to disasters: a pre-emptive approach. *Engineering, Construction and Architectural Management*, *14*(5), 434-446.

Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., & von Winterfeldt, D. (2003). A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake Spectra*, *19*(4), 733-752.

Çakir, O. (2008). The grey extent analysis. *Kybernetes*, *37*(7), 997-1015.

Chen, Y., McCabe, B., & Hyatt, D. (2017). Relationship between individual resilience, interpersonal conflicts at work, and safety outcomes of construction workers. *Journal of Construction Engineering and Management*, *143*(8), 04017042.

Chmutina, K., & Rose, J. (2018). Building resilience: knowledge, experience and perceptions among informal construction stakeholders. *International Journal of Disaster Risk Reduction*, *28*, 158-164.

Dong, Y., & Xu, J. (2018). *Linguistic decision making: numerical scale model and consistency-driven methodology*. Springer.

Emmanuel, R., & Krüger, E. (2012). Urban heat island and its impact on climate change resilience in a shrinking city: the case of Glasgow, UK. *Building and Environment*, *53*, 137-149.

Grimm, D. A., Gorman, J. C., Cooke, N. J., Demir, M., & McNeese, N. J. (2023). Dynamical measurement of team resilience. *Journal of Cognitive Engineering and Decision Making*, *17*(4), 351-382.

Hartwig, A., Clarke, S., Johnson, S., & Willis, S. (2020). Workplace team resilience: a systematic review and conceptual development. *Organizational Psychology Review*, *10*(3-4), 169-200.

Harvey, E. J., Waterson, P., & Dainty, A. R. (2019). Applying HRO and resilience engineering to construction: barriers and opportunities. *Safety Science*, *117*, 523-533.

Hassler, U., & Kohler, N. (2014). Resilience in the built environment. *Building Research & Information*, *42*(2), 119-129.

Hatton, T., Seville, E., & Vargo, J. (2012). Asia Pacific Economic Cooperation (APEC) project on the Canterbury Earthquake series and SME resilience. *Report 7: improving the resilience of SMEs: policy and practice in New Zealand*. University of Canterbury.

Huber, M. (2023). *Resilience in the team: ideas and application concepts for team development*. Springer Nature.

Gucciardi, D. F., Crane, M., Ntoumanis, N., Parker, S. K., Thøgersen-Ntoumani, C., Ducker, K. J., & Temby, P. (2018). The emergence of team resilience: a multilevel conceptual model of facilitating factors. *Journal of Occupational and Organizational Psychology*, *91*(4), 729-768.

Jadidi, O., Sai Hong, T., Firouzi, F., & Yusuff, R. M. (2009). An optimal grey based approach based on TOPSIS concepts for supplier selection problem. *International Journal of Management Science and Engineering Management*, *4*(2), 104-117.

John, M. A. (2014). Embedding built environments in social–ecological systems: resilience-based design principles, *Building Research & Information*, *42*(2), 130-142.

Khurami, E. A. (2015). İnşaat sektörünün dayanıklılığını konut sunumunun ötesinde aramak. *Resilience*, *3*(2), 217-227.

Kurth, M. H., Keenan, J. M., Sasani, M., & Linkov, I. (2019). Defining resilience for the US building industry. *Building Research & Information*, *47*(4), 480-492.

Liu, S., Lin, Y., Liu, S., & Lin, Y. (2011). Introduction to grey systems theory. In *Grey systems: theory and applications* (pp. 1-18).

Love, P. E., & Matthews, J. (2020). Quality, requisite imagination and resilience: managing risk and uncertainty in construction. *Reliability Engineering & System Safety*, *204*, 107172.

Nemeth, C., Wears, R. L., Patel, S., Rosen, G., & Cook, R. (2011). Resilience is not control: healthcare, crisis management, and ICT. *Cognition, Technology & Work*, *13*, 189-202.

Parvin, G. A., & Shaw, R. (2011). Climate disaster resilience of Dhaka City Corporation: an empirical assessment at zone level. *Risk, Hazards & Crisis in Public Policy*, *2*(2), 1-30.

Peñaloza, G. A., Saurin, T. A., & Formoso, C. T. (2020). Monitoring complexity and resilience in construction projects: the contribution of safety performance measurement systems. *Applied Ergonomics*, *82*, 102978.

Rutter, M. (2012). Resilience as a dynamic concept. *Development and Psychopathology*, *24*(2), 335-344.

Sapeciay, Z., Wilkinson, S., Costello, S. B., & Adnan, H. (2019). Building organisational resilience for the construction industy: strategic resilience indicators. *IOP Conference Series: Earth and Environmental Science, 385*(1), 012068.

Stoverink, A. C., Kirkman, B. L., Mistry, S., & Rosen, B. (2020). Bouncing back together: toward a theoretical model of work team resilience. *Academy of Management Review*, *45*(2), 395-422.

Yang, J., & Cheng, Q. (2020). The impact of organisational resilience on construction project success: evidence from large-scale construction in China. *Journal of Civil Engineering and Management*, *26*(8), 775-788.

Walker, B., & Salt, D. (2006). *Resilience thinking: sustaining ecosystems and people in a changing world*. Island Press, Washington.

Wang, D., Wu, Y., & Zhang, K. (2023). Interplay of resources and institutions in improving organizational resilience of construction projects: a dynamic perspective. *Engineering Management Journal*, *35*(4), 346-357.

Wedawatta, G., Ingirige, B., & Amaratunga, D. (2011). Case study as a research strategy: investigating extreme weather resilience of construction SMEs in the UK. *Proceedings of 7th Annual International Conference of International Institute for Infrastructure, Renewal and Reconstruction*.

Wehbe, F., Al Hattab, M., & Hamzeh, F. (2016). Exploring associations between resilience and construction safety performance in safety networks. *Safety Science*, *82*, 338-351.

Wilkinson, S., Chang-Richards, A. Y., Sapeciay, Z., & Costello, S. B. (2016). Improving construction sector resilience. *International Journal of Disaster Resilience in the Built Environment*, *7*(2), 173-185.

Exploring Urban Resilience: A Socio-spatial Perspective of the Adaptive Reuse Projects in İstanbul, Turkey

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Abstract

In the dynamic urban fabric of Istanbul, the concept of adaptive reuse has gained significant attention as a sustainable approach to urban development. While the physical transformation of historic structures through adaptive reuse projects has been widely discussed, the socio-spatial implications of such initiatives of resilience, capacity building for local communities, well-being, and livability remain relatively understudied by the stakeholders. This study aims to examine the multifaceted dynamics of social resilience within the context of adaptive reuse projects in Istanbul, Turkey. By exploring the social dynamics surrounding these adaptive reuse projects, this research intends to shed light on the evolving narratives of communities' social resilience and socio-cultural sustainability within the rapidly transforming urban landscape of Istanbul. This research contributes to the discourse on sustainable and socially resilient urban development by emphasizing the significance of fostering community engagement as an integral component of adaptive reuse initiatives that are involved in the preservation of cultural heritage and the sustainable revitalization of urban spaces.

Keywords: *adaptive reuse projects, capacity building, community engagement, empowerment, socio-spatial sustainability.*

Introduction

In the ever-expanding landscape of urbanization worldwide, the fusion of urban resilience and sustainability emerges as a critical focal point demanding our immediate attention. This paper explores the dynamic relationship between urban resilience and sustainability, specifically focusing on the role of social resilience within adaptive reuse spaces. Adaptive reuse, a sustainable practice that repurposes existing structures, offers a unique lens through which to examine the intertwined concepts of urban resilience and sustainability. By investigating the social dimensions of adaptive reuse spaces, this paper aims to contribute to a holistic understanding of how urban environments can foster resilience while promoting sustainable development. The increasing pace of urbanization has spurred a growing interest in creating cities that are not only sustainable but also resilient to various challenges. Urban resilience and sustainability, though distinct concepts share common ground in fostering cities that can withstand stresses while maintaining social, economical, and ecological balance. This paper aims to explore the synergies between specifically two concepts, with a particular emphasis on the social dimensions within the context of adaptive reuse spaces. Urban resilience and sustainability have a symbiotic relationship. Urban resilience encompasses the capacity of cities to adapt, recover, and transform in the face of disturbances. Sustainability, on the other hand, focuses on meeting the needs of the present without compromising the ability of future generations to meet their own needs. Together, these concepts create an interrelation, as resilient cities are better equipped to sustain themselves in the long term. This section will delve into the interconnections between urban resilience and sustainability, emphasizing the importance of a comprehensive approach to urban development through adaptive reuse projects.

In this study, we would like to point out the interrelation of architectural preservation practice with responsible and prudential urban regeneration. Adaptive reuse involves repurposing existing structures for new functionalities, minimizing environmental impact, and preserving cultural heritage. The adaptive reuse of structures contributes to sustainable urban development by maximizing the use of existing resources. Moreover, this study explores the sustainable aspects of adaptive reuse, including the preservation of historical identity and urban memory and its social dimensions. The social fabric of urban communities plays a crucial role in building resilience. Adaptive reuse spaces, by their nature, engage local communities, fostering a sense of place and identity. This study investigates how adaptive reuse projects can enhance social resilience through community engagement, inclusivity, and the creation of vibrant, multi-functional spaces that adapt to the evolving needs of diverse populations. While the integration of urban resilience, sustainability, and social resilience in adaptive reuse spaces presents immense opportunities, it also comes with challenges. In conclusion, this paper underscores the importance of integrating urban resilience and sustainability, with a specific focus on social resilience in adaptive reuse spaces. By understanding and harnessing the synergies between these concepts, cities can aspire to create environments that are not only sustainable and resilient but also socially inclusive and adaptive to the ever-changing needs of their inhabitants. This holistic approach is essential for shaping urban spaces that thrive in the face of uncertainty while fostering a sense of community and belonging. As a case study, we examined ten completed adaptive reuse projects that were accomplished in İstanbul, Turkey. Those case studies illustrate the interplay of the socio-spatial dimension of urban resilience. Drawing on real-world examples, this section analyzes case studies that exemplify the intricate relationship between urban resilience, sustainability, and social resilience in adaptive reuse spaces. Examining successful projects will provide insights into the practical implementation of these concepts and offer lessons for future urban development.

Literature Review

Resilience is a concept that is addressed by different disciplines and is fundamentally linked to sustainability. It first entered the literature in the 1970s with the ‘ecological system’ research of Holling (1973). According to this study, a resistant system can repair itself, return to its previous state, or maintain its current state against the dangers and disruptions it encounters. In this context, Holling matches resilience with the concept of durability, constancy, and stability. However, in the following studies related to social systems (Folke et al., 2010) the concept of resilience was discussed more in connection with the definitions of flexibility and adaptability. According to this study, the characteristics of a resistant system are adapting to the dangers, finding balance, being flexible, and adapting to the new order. Eventually, it can be said that the system can become more resilient when it adapts to the new order and provides flexibility, rather than insisting on preserving its old state against the disruption it encounters. Resilience is generally considered the capacity to tolerate, absorb, cope with, and adjust to changing social or environmental conditions while retaining key elements of structure, function, and identity.

The social dimensions of resilience are vital to understanding the impacts of environmental changes, such as climate change, on social-ecological systems. Resilience has become a central concept in the field of architecture and the built environment due to the increasing frequency and severity of natural disasters, coupled with the challenges posed by climate change, urbanization, and social dynamics (Cutter et al., 2014). On the other hand, the concept of resilience in the built environment has gained significant attention, particularly when viewed through the lens of sustainable materials. This perspective highlights the critical role of materials in enhancing the ability of structures and urban spaces to withstand disturbances and contribute to long-term sustainability.

Physical resilience involves the ability of structures and infrastructure to withstand shocks and stresses, such as earthquakes, hurricanes, and flooding (Bozza et al., 2017). Chelleri et al. (2012) argue that social resilience involves the adaptive capacity of communities to cope with and recover from disruptions. This involves examining social networks, community cohesion, and inclusivity as crucial components of urban resilience. Spatial factors play a pivotal role in urban resilience. These include the use of sustainable and resilient materials, innovative construction techniques, energy-efficient design, and the integration of smart technologies (Ratti & Townsend, 2011). Social resilience pertains to the capacity of communities to adapt and bounce back from disruptions, while ecological resilience concerns the sustainability and adaptability of natural systems within urban environments. Researchers and practitioners have outlined several principles of resilient design, emphasizing flexibility, redundancy, and adaptability (Pelling, 2003). These principles stress the importance of designing buildings and cities that can function under changing conditions, accommodating evolving needs and technological advancements. Additionally, urban planning and zoning regulations play a crucial role in promoting resilience by encouraging mixed land uses, protecting green spaces, and ensuring robust transportation networks (Iwaro & Mwasha, 2010). Numerous case studies in the literature provide real-world examples of resilient architecture and urban design, and these case studies often focus on projects that have successfully integrated resilience principles into their designs, such as flood-resistant buildings, resilient infrastructure, and disaster-resilient communities. Examining these cases offers valuable insights into the practical application of resilience concepts. While the concept of resilience is gaining traction in architecture and the built environment, there are several challenges and barriers to its widespread adoption. These include financial constraints, regulatory hurdles, lack of awareness, and the need for interdisciplinary collaboration between architects, engineers, urban planners, and policymakers (World Bank, 2016; United Nations, 2015). The literature on resilience in architecture and the built environment underscores the importance of designing structures and cities that can withstand and recover from various challenges.

Case Study Outcomes

According to The OECD report (2014), the concept of resilience is discussed in four dimensions: environment, economy, society, and governance. Therefore, it is applied as a categorization that can be used for the urban resilience analysis scale for this study.

In Table 1, the documentation of the ten successfully completed adaptive reuse projects in Istanbul is shown. The outcomes of those projects will be discussed in the next section of this paper.

Table 1. Case studies are explained in this table with categories and references.

	Project	**Location**	**Previous Function**	**Adaptive Reuse Function**	**Category 1: Environment**		**Category 2: Economy**		**Category 3: Society**		**Category 4: Governance**		**Result**
					Management Strategy	Local Materials and Resources	Employment	Production and Circular Economy	Capacity Building & Inclusion	Empowerment and Engagement	Citizen Design Science	Responsive Governance	
1	**Casa Botter (public owner)**	İstiklal Street, *Beyoğlu*	Built as residential complex and fashion house (1900)	Coworking space, arts & cultural center (2023)	-	+	+	-	+	+	+	+	• Policy Frameworks and Governance • Community Engagement and Empowerment • Cultural Identity and Social Cohesion • Socio-Economic Impacts and Well-being
2	**Metrohan (public owner)**	İstiklal Street, *Beyoğlu*	Built as metro station (1874) Operated as an administration office for public transportation (1914)	Coworking space, library, arts & cultural center (2023)	-	+	+	-	+	+	+	+	• Policy Frameworks and Governance • Community Engagement and Empowerment • Cultural Identity and Social Cohesion • Inclusive Design and Accessibility • Socio-Economic Impacts and Well-being
3	**Gazhane (public owner)**	Hasanpaşa Street, *Kadıköy*	Built as a gasworks to produce coal gas (1892)	Arts, cultural center and technology museum (2021)	+	+	+	+	+	+	+	+	• Policy Frameworks and Governance • Community Engagement and Empowerment • Cultural Identity and Social Cohesion • Socio-Economic Impacts and Well-being
4	**Moda İskelesi (public owner)**	Caferağa Street, *Kadıköy*	Built as a ship pier (1917)	Library and Café (2022)	-	+	+	+	+	+	+	+	• Policy Frameworks and Governance • Community Engagement and Empowerment • Cultural Identity and Social Cohesion • Inclusive Design and Accessibility. • Socio-Economic Impacts and Well-being
5	**Taş Mektep (public owner)**	Kadıyoran Street, *Büyükada*	Built as residential complex (1870) Operated as a primary school (1922)	Library, arts & cultural center (2024)	-	+	+	-	+	+	+	+	• Policy Frameworks and Governance • Community Engagement and Empowerment • Cultural Identity and Social Cohesion • Inclusive Design and Accessibility • Socio-Economic Impacts and Well-being
6	**Salt Galata (private owner)**	Bankalar Street, *Beyoğlu*	Built as a Bank (1892)	Library, arts & cultural center (2011)	-	+	+	-	+	+	-	-	• Policy Frameworks and Governance • Community Engagement and Empowerment • Cultural Identity and Social Cohesion • Inclusive Design and Accessibility • Socio-Economic Impacts and Well-being
7	**Sakıp Sabancı Müzesi (private owner)**	Sakıp Sabancı Street, *Emirgan*	Built as residential complex (1927)	Art Museum & cultural center (2002)	-	+	+	-	+	+	-	-	• Policy Frameworks and Governance • Community Engagement and Empowerment • Cultural Identity and Social Cohesion • Inclusive Design and Accessibility • Socio-Economic Impacts and Well-being
8	**Bomontiada (private owner)**	Silahşör Street, *Şişli*	Built as a beer factory (1927)	Social & cultural center (2018)	-	+	+	+	+	+	-	-	• Community Engagement and Empowerment • Inclusive Design and Accessibility • Socio-Economic Impacts and Well-being
9	**Beykoz Kundura (private owner)**	Süreyya İlmen Street, *Beykoz*	Built as a shoe factory (1800)	Art & cultural center (2004)	-	+	+	+	+	+	-	-	• Inclusive Design and Accessibility • Socio-Economic Impacts and Well-being
10	**Fişekhane (private owner)**	Kennedy Street, *Zeytinburnu*	Built as an explosive manufacture complex (1840)	Social & cultural center (2020)	-	+	+	+	+	+	-	-	• Community Engagement and Empowerment • Inclusive Design and Accessibility • Socio-Economic Impacts and Well-being

Discussion

Based on the breakdown presented in Table 1 of the case study analysis, it is evident that the applied projects have resulted in socially resilient adaptive reuse initiatives that effectively met their objectives both in structural, functional, and social perspectives. Substantial evidence supports the majority of positive outcomes observed across the four categories during the implementation and subsequent operation of these projects upon their completion. Moreover, the interpretation of the key social factors outlined earlier is consolidated, indicating a positive impact on community well-being and empowerment across all projects. Consequently, it can be inferred that these initiatives serve as exemplary instances of capacity-building for the communities, contributing to their socio-spatial, and socio-economic resilience. The list above showcases diverse perspectives and interdisciplinary approaches that contribute to a comprehensive understanding of the complex interplay between adaptive reuse projects and social resilience.

1. Policy Frameworks and Governance: Mérai et al. (2022) underscore the importance of robust policy frameworks and effective governance structures in promoting the successful implementation of adaptive reuse projects. Their research emphasizes the need for comprehensive policy interventions that prioritize the preservation of cultural heritage, community well-being, and sustainable urban development, fostering a conducive environment for the enhancement of social resilience within the context of adaptive reuse projects. Additionally, various studies examine the role of governance structures in facilitating community participation and collaborative decision-making processes, highlighting the significance of transparent and inclusive governance mechanisms in ensuring the long-term social resilience and sustainability of adaptive reuse projects.

2. Community Engagement and Empowerment: Barani and Dastranj (2023)emphasize the critical role of community engagement in fostering social resilience through adaptive reuse projects. Their work advocates for participatory design processes that empower local communities and foster a sense of ownership and collective responsibility for the revitalization of urban spaces. Building on this, the research highlights the significance of community-led initiatives in adaptive reuse projects, underscoring how grassroots efforts and participatory decision-making processes contribute to the social resilience and sustainable development of urban neighborhoods. Additionally, during the operation stage of the project, the adapted functions should serve public needs and demands.

3. Cultural Identity and Social Cohesion: Mousavinia (2024) highlights the significance of adaptive reuse projects in preserving cultural heritage and fostering social cohesion within diverse communities. Their findings underscore how the adaptive transformation of historical structures into vibrant cultural hubs nurtures a sense of cultural identity, pride, and belonging among the residents, thereby strengthening the social fabric and resilience of the neighborhoods. Similarly, the work of Fabi et al. (2021) delves into the cultural significance of adaptive reuse projects, emphasizing the role of cultural preservation in fostering intergenerational connections and social cohesion within the context of urban regeneration initiatives. Moreover, inclusive design and accessibility concepts emphasize the importance of inclusive design practices in adaptive reuse projects. Their research underscores the transformative potential of architectural interventions that prioritize universal design principles, fostering social inclusivity, equality, and accessibility within the transformed urban environments. Furthermore, various studies highlight the role of inclusive design in promoting

accessibility for individuals with diverse abilities, emphasizing the need for architectural interventions that cater to the specific needs and preferences of all community members.

4. Socio-Economic Impacts and Well-being: Lundgreen (2023) explores the psychosocial well-being impacts of adaptive reuse projects. Their research delves into the psychological and emotional dimensions of community transformation, shedding light on how adaptive reuse initiatives can contribute to the enhancement of mental health and social interconnectedness within urban populations. Munaro et al. (2020) investigate the socio-economic impacts through the circular economy perspective of adaptive reuse projects; on the well-being and livelihoods of local communities. Their research highlights the potential of adaptive reuse initiatives to stimulate economic growth, create employment opportunities, and improve the overall quality of life for residents, thereby contributing to the social resilience and sustainable development of urban neighborhoods. Similarly, various research examines the social and economic benefits of adaptive reuse projects in marginalized communities, emphasizing the potential for these initiatives to address social inequalities and foster equitable development within urban environments. Moreover, the work of Cinderby et al. (2016), investigates the role of adaptive reuse projects in promoting community resilience and well-being, emphasizing the therapeutic benefits of community engagement and cultural revitalization in fostering a sense of belonging and social support within urban neighborhoods.

By synthesizing these diverse perspectives, the literature underscores the interconnected nature of social resilience, community empowerment, cultural preservation, and inclusive governance within the realm of adaptive reuse projects. The existing body of research highlights the transformative potential of adaptive reuse initiatives in fostering socially resilient and vibrant urban communities, underscoring the need for holistic and participatory approaches to sustainable urban development and architectural revitalization. Urban resilience has evolved beyond a mere focus on infrastructure to encompass the social and spatial dimensions of cities. Scholars such as Meerow et al. (2016) argue that resilience cannot be solely understood through the lens of physical infrastructure; instead, it must integrate the social fabric and spatial configurations of urban areas. Therefore, a holistic understanding of urban resilience requires an integration of social and spatial dynamics. Pickett et al. (2014), proposes a socio-ecological resilience framework that recognizes the interdependence of social and ecological systems in urban areas. This approach emphasizes the need to consider social structures alongside physical landscapes in resilience planning. Community participation and effective governance emerge as critical elements in socio-spatial urban resilience. Berkes and Ross (2013) argue that involving communities in decision-making processes fosters social capital and strengthens the resilience of urban systems. Effective governance structures ensure that spatial planning aligns with the diverse needs and vulnerabilities of different social groups. Addressing socio-spatial resilience requires an examination of vulnerability and inequality within urban contexts. Despite progress, challenges persist in implementing socio-spatial urban resilience. Some research, such as Leichenko and O'Brien (2008), highlights the need for further interdisciplinary collaboration, data integration, and policy innovation to address the complexities of socio-spatial dynamics in urban resilience. Socio-spatial urban resilience represents a paradigm shift in understanding and addressing the challenges faced by cities. By integrating social and spatial dimensions, urban planners and policymakers can develop more robust strategies that not only enhance the physical infrastructure but also promote social inclusivity, reduce inequality, and empower communities to adapt and thrive in the face of urban uncertainties.

Further research and practical applications are crucial to refining the theoretical foundations and effectively implementing socio-spatial urban resilience strategies. Resilient urban planning and infrastructure are fundamental to ensuring the safety and well-being of city residents (UN Habitat, 2018). They attract businesses and talent, creating more opportunities for employment and economic growth (Glaeser & Resseger, 2010). Therefore, the betterment of the local economy empowers the community. These innovative approaches not only contribute to the sustainability and resilience of cities but also have a direct impact on enhancing the livability of urban areas. By incorporating these elements into urban planning and design, cities can become more resilient, sustainable, and livable. In an era of rapid urbanization, this integrated approach holds the key to creating cities that are both thriving and resilient. Examining the correlation between social resilience and adaptive reuse projects uncovers an essential factor that emphasizes the profound influence of these endeavors on urban communities.

Conclusion

This study reviewed the multifaceted dynamics of social resilience within the context of adaptive reuse projects in Istanbul, Turkey. The contribution of this paper lies in its preliminary endeavor to establish a universal assessment criterion within the socio-spatial resilience framework, facilitated by the application of the scale utilized.

Resilience is a multifaceted concept that involves physical, social, and ecological dimensions, and its principles and strategies are evolving as researchers and practitioners continue to explore innovative approaches. The level of resilience affects the sustainability of the city. While challenges exist, the growing recognition of resilience as a critical component of sustainable design is driving efforts to create more resilient and adaptable built environments. Any place, event, or individual can be defined instead of the concept of the system when explaining the resilience approach. Urban resilience is directly related to sustainability and well-being. Therefore; in this study, the concept of resilience will be discussed in a spatial context concerning social aspects. Moreover, urban resilience means that the city adapts to change and maintains its continuity, ensuring sustainability. Social resilience increases the society's sense of being a society, belonging, cultural identity, and social adaptation ability, and creates a more conscious, active, collective, and learning community, therefore it also accelerates the success of the adaptive reuse project.

The study deals with the concept of resilience in a spatial context and is examined with the discipline of historic preservation and architectural adaptive reuse projects, which consider the interaction between people and space. For this reason, the social dimension of resilience is the focus point of this study. In this context, social resilience is assessed by criteria based on a literature review.

Social inclusion plays a pivotal role in shaping socio-spatial resilience within urban contexts. When communities are inclusive, where individuals of diverse backgrounds are integrated and valued, it fosters social cohesion and solidarity. This cohesion forms a strong foundation for resilience, enabling communities to withstand and recover from various challenges such as economic downturns, natural disasters, or social conflicts. Inclusive urban spaces not only provide equitable access to resources and opportunities but also cultivate networks of support and mutual aid. Such networks become vital during times of stress, change, and inconvenience, facilitating collective responses and adaptive strategies. Conversely, exclusion and marginalization breed vulnerability, undermining the resilience of urban areas by creating divides that weaken social bonds and hinder collaborative efforts. Therefore, fostering social inclusion is not only a matter of equity and justice but also an essential factor for creating livable environments and a fundamental aspect of building resilient urban communities capable of thriving in the face of adversity.

References

Barani, M., & Dastranj, F. (2023). Participatory design in interior architecture; A proposal for the factors of adaptive reuse with user participation. *SAUC - Journal, 9*(1).

Berkes, F., & Ross, H. (2013). Community resilience: Toward an integrated approach. *Society & Natural Resources, 26*(1), 5-20.

Bozza, A., Asprone, D., & Manfred, G. (2017). Physical resilience in cities. *Natural Hazard Science*.

Chelleri, L., Waters, J., Olazabal, M., & Minucci, G. (2012). Resilience trade-offs: Addressing multiple scales and temporal aspects of urban resilience. *Environment and Urbanization, 27*(1), 181-198.

Cinderby, S., Haq, G., Cambridge, H., & Lock, K. (2016). Building community resilience: Can everyone enjoy a good life? *Local Environment, The International Journal of Justice and Sustainability*, 1252-1270.

Cutter, S., Ash, K., & Emrich, C. (2014). The geographies of community disaster resilience. *Global Environmental Change, 29*, 65-77.

Fabi, V., Vettori, M., & Faroldi, E. (2021). Adaptive reuse practices and sustainable urban development: Perspectives of innovation for European historic spa towns. *Sustainability, 13*, 5531.

Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L., & Chapin, F. (2010). Resilience thinking: Integrating resilience, adaptability and transformability: Ecosystem-based design. *Ecology and Society, 15*(4).

Glaeser, E., & Resseger, M. (2010). The complementarity between cities and skills. *Journal of Regional Science, 50*(1), 221-244.

Holling, C. (1973). Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics, 4*, 1-23.

Iwaro, J., & Mwasha, A. (2010). A review of building energy regulation and policy for energy conservation in developing countries. *Energy Policy, 38*(12), 7744-7755.

Leichenko, R., & O'Brien, K. (2008). *Environmental change and globalization: Double exposures.* London: Oxford University Press.

Lundgreen, R. (2023). Social life cycle assessment of adaptive reuse. *Buildings and Cities, 4*(1), 334–351.

Meerow, S., Newell, J., & Stults, M. (2016). Defining urban resilience: A review. *Landscape and Urban Planning, 147*, 38-49.

Mérai, D., Veldpaus, L., Pendlebury, J., & Kip, M. (2022). The governance context for adaptive heritage reuse: A review and typology of fifteen European countries. *The Historic Environment: Policy & Practice, 13*(4), 526–546.

Mousavinia, S. (2024). Changes in social impacts of industrial heritage adaptive reuse in high-density residential environment: Reciprocal relations between social cohesion and perceived safety. *Social Indicators Research, 172,* 59–80.

Munaro, M., Tavares, S., & Bragança, L. (2020). Towards circular and more sustainable buildings: A systematic literature review on the circular economy in the built environment. *Journal of Cleaner Production, 260*.

OECD. (2014). *Overview Paper On Resilient Economies And Societies.* Paris: OECD.

Pelling, M. (2003). *The vulnerability of cities: Natural disasters and social resilience.* Earthscan Publications Ltd.

Pickett, S., Cadenasso, M., & Grove, J. (2014). Resilient cities: Meaning, models, and metaphor for integrating the ecological, socio-economic, and planning realms. *Landscape and Urban Planning, 147,* 3-12.

Ratti, C., & Townsend, A. (2011). *The social nexus: Cities, big data, and the end of privacy.* Boston: MIT.

UN Habitat. (2018). *The state of Asian and Pacific cities 2018: Expanding opportunities in a rapidly urbanizing world.* United Nations Human Settlements Programme.

United Nations. (2015). *Sendai framework for disaster risk reduction.* UN.

World Bank. (2016). *Building regulation for resilience: Making cities safer through building codes.* World Bank.

Role of Spontaneous Volunteers for Community Resilience: Lessons Learned from the Southeastern Anatolia Earthquake Temporary Structures Project

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Abstract

The global increase in natural and human-induced disasters emphasizes the necessity for temporary structures. This study examines the construction processes of such temporary units initiated by spontaneous volunteers during disaster situations, with a focus on their impact on societal resilience. The backdrop of the devastating 2023 earthquakes in Turkey highlights the urgency of this research. This research aims to investigate the participation of spontaneous volunteers in producing shelter units for earthquake survivors during the disaster process to transfer lessons learned to future research endeavors.

This research underscore the impact and importance of spontaneous volunteers on societal resilience during disaster situations. To achieve this objective, the study focuses on the construction process of a project initiated by volunteers due to the need for temporary units. Utilizing the participant observer research method, the study observed the project's process in the field, collected data, and presented findings supported by literature research. Despite encountering challenges in project management, coordination, communication, and training, opportunities such as collaboration, solidarity, and a conducive learning environment were observed. While tangible benefits from spontaneous volunteers emerged, this study emphasizes the identified challenges, highlighting the necessity for future research to enhance societal resilience against potential disaster situations.

Keywords: *Southeastern Anatolia earthquake, community resilience, spontaneous volunteering, temporary structures, project management, disaster response*

Introduction

The Earth is a devastating and degraded place due to anthropogenic, natural and hybrid disasters (Finsterwalder et al., 2024). The world is becoming more vulnerable daily due to the increasing frequency, duration and intensity of expected or unexpected disasters (Chen et al., 2021). Therefore, simultaneously and randomly, temporary buildings were needed worldwide (Chen et al., 2021). Many temporary structures have been built, such as the Fangcang shelter hospitals, which were quickly established in China due to the COVID-19 epidemic in 2020 (Chen et al., 2020), and the temporary shelter units established after the earthquake in Turkey in 1999 (Arslan, 2007). The focus is mainly on the construction of temporary structures quickly and in a short time due to the urgent need for shelter (Chen et al., 2021). The importance of this need is clearly seen after the Southeastern Anatolia earthquakes of February 6, 2023.

In accordance with the data provided by AFAD (Disaster and Emergency Management Authority), on February 6, 2023, at 04:17 local time, Turkey experienced a seismic event registering a magnitude of 7.7, with its epicenter located in Pazarcık. Subsequently, approximately nine hours later, another earthquake of magnitude 7.6 occurred, with its epicenter in Elbistan, within the vicinity of Kahramanmaraş. These seismic activities had profound ramifications across several provinces, notably Kahramanmaraş, Hatay, Gaziantep, Malatya, Diyarbakır, Kilis, Şanlıurfa, Adıyaman, Osmaniye, Adana, and Elazığ. Moreover, Bingöl, Kayseri, Mardin, Tunceli, Niğde, and Batman provinces were designated as disaster areas. It is imperative to note that these seismic events represent some of the deadliest natural disasters witnessed in Turkey during this century. Official statistics indicate a staggering loss of life, with 50,783 fatalities recorded, alongside 115,353 individuals sustaining injuries, and the collapse of 37,984 structures documented. This calamitous event underscores the multifaceted adverse impacts of natural disasters. The response to unexpected impacts tests community resilience. (Chen et al., 2021). Community resilience is a critical concept during disaster (Ji, 2018). Imperiale and Vanclay (2016) define "community resilience" as a complex of social processes that enable local communities to self-organize and engage in positive collective action for the survival and well-being of the community. Therefore, this research aims to highlight the impact and significance of spontaneous volunteers on community resilience during disaster situations. Accordingly, this research focuses on spontaneous volunteers actively involved in the construction process of temporary structures needed by earthquake survivors.

Community Resilience

The origin of the word "resilience" comes from the Latin word "resilire" (Timmerman, 1981) that is a combination of re- "back" and salire "to jump, leap". The word resilience was used to mean "act of rebounding" in the 1620s, and in 1824s it began to mean "flexibility" (Online Etymology Dictionary, 2020). This concept of flexibility was first used in the 1800s to describe the strength (rigidity) and deformation (ductility) of steel elements, and in this sense it is now known as engineering resilience (Alexander, 2013). Merriam-Webster (2020) describes resilience from engineering as "the capability of a strained body to recover its size and shape after deformation caused especially by compressive stres". In the 1970s, it was used as ecological resilience for regeneration, reorganization, and continuous improvement (Holling, 1973). It also has a long history in behavioral sciences, up to clinical and developmental psychology research in the 1970s (Anthony, 1974; Garmezy & Masten, 1986), with its use in psychology to describe the capacity of a child suffering from schizophrenia to withstand shock (Masten et al., 1990). In this context, the word resilience is defined at present as "the ability to be happy, successful, etc. again after something difficult or bad has happened" or "the quality of being able to return quickly to a previous good condition after problems" (Cambridge Online Dictionary, 2020). Furthermore, resilience is the process and capacity that enables individuals or human, technical or natural systems to overcome, resist, adapt and recover from deep crises (Juvet et al., 2021). Therefore, there is no universal definition of resilience (Knight, 2007), and it contains definitions specific to the discipline in which it is used (Windle, 2011).

This research focuses on defining the concept of resilience in disaster situations. Graveline and Germain (2022), state that there is no real consensus on the definition of resilience in disaster management. However, the most widely recognized definition is *"the ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management"*, which is the definition of the United Nations Office for Disaster Risk Reduction (UNDRR). Building community resilience is one of the keys to reducing disaster risks (Ji, 2018). Society often takes spontaneously organized action when the state and the market cannot cope, and community participation is central in dealing with disasters (Mauroner & Heudorfer, 2016). Disaster resilience depends on the community because of the importance of the local scale (Graveline & Germain, 2022).

Spontaneous Volunteering

Volunteering encompasses any activity where time is freely given to benefit others (Wilson, 2000). Four fundamental characteristics define an activity as volunteering: the decision to volunteer, absence of coercion, participation in the activity, and an organizational context (Penner, 2004). Volunteers engage in assistance activities of their free choice without expecting any reward or compensation throughout this time-spanning process (Snyder & Omoto, 2008). According to the United Nations Volunteers (UNV) programme report (2021), the economic impact of millions of volunteers participating in various sectors is equivalent to approximately 61,000,000 full-time employees assuming a 40-hour workweek per month. Numerous examples exist where emergencies and disasters overwhelm a country's intervention capacity (Yukseler & Yazgan, 2022). Hence, ordinary citizens, not affiliated with official institutions, who voluntarily dedicate their time, knowledge, skills, and resources to help others during crises, are crucial human resources in disaster situations. These human resources not affiliated with official institutions are described by various terms such as "informal," "unaffiliated," and "spontaneous" volunteers (Whittaker et al., 2015). In this research, these volunteers are referred to as spontaneous volunteers.

Participant Observation Method

This research focuses on a project initiated by volunteers to address the housing needs of earthquake survivors affected by the February 6 earthquakes. The aim is to examine the impact of spontaneous volunteers on community resilience during the disaster process by taking a case study approach. Participant observation method was employed for field research. Field research involves the researcher being present in the field primarily through participant observation or interviews to collect data firsthand (Chou & Wu, 2014).

A case study is one of the most common qualitative research strategies preferred in situations where understanding a phenomenon in its natural setting, without isolating it from its context, focusing on current events, and valuing the actors’ experiences are important (Myers & Avison, 2002). Participant observation is one of the main methods used in case studies (Iacono et al., 2009). Participant observation research method aims to explore the phenomenon to be investigated through observation and participation, utilizing the researcher's self as a tool (Rock & Rock, 1979). Participant observation is critical for data collection and analysis in the implementation of social science research to ensure continuity in research amidst changing situations and environments (Chou & Wu, 2014). Rather than quantitative methods like survey research, qualitative research methods such as participant observation are considered more suitable for studying social events because textual data loses its meaning when quantified, hindering the understanding of a phenomenon from the actors' perspective (Iacono et al., 2009).

The participant observation research method is increasingly being used in organizational research. There are two approaches in organizational research: "outsider inquiry" and "insider inquiry." Outsider inquiry involves collecting data by observing organizational data from an external perspective. In contrast, insider inquiry involves personal involvement in the organization as part of the research approach to collect data. According to researchers, data obtained through an insider inquiry approach is considered more valid and meaningful (Iacono et al., 2009). Therefore, this study adopts the insider inquiry research approach.

This research aims to examine the participation of spontaneous volunteers in the production of housing units for earthquake survivors during the disaster process using the participant observation research method, to be involved in field applications, interpret the collected data, and transfer the lessons learned to future research endeavors.

This research presents a case study of a project that commenced in mid-February in Istanbul intending to construct 100 shelters for earthquake victims within a month. After 2.5 months, the produced units were relocated to Hatay, one of the earthquake-stricken regions. These shelters were made available for occupancy in October 2023 to accommodate individuals needing housing. As of April 2024, volunteer efforts are ongoing to improve the project and provide better living conditions for earthquake victims. The call for volunteer support for this project was primarily made through social media channels, resulting in approximately 4000 volunteers offering assistance, and materials being collected within two days. The lead author of this study also became aware of the project through social media and volunteered for fieldwork, dedicating a minimum of 30 hours per week for about two months. Following the relocation of the living units, the researcher spent three days in the earthquake-affected area observing and supporting the project.

Volunteers worldwide are increasingly establishing closer partnerships with government officials to address issues in emergencies such as the impacts of the COVID-19 pandemic (UNV, 2021). In this project, in response to the request from initiating volunteers, the municipality in Istanbul provided a large indoor space for the construction of temporary shelters to meet the need for space. The location in Hatay, where the constructed shelters would be situated, was determined through discussions and agreements with government authorities.

Spontaneous volunteers are individuals who, in disaster situations, are not formally connected to intervention and rescue systems, and may or may not possess information, education, skills, and experience about the activities to be undertaken (Whittaker et al., 2015). The spontaneous volunteers involved in this project include university students, craftsmen, construction workers, search and rescue teams, yoga instructors, artists, architects, engineers, mechanics, and tradespeople, representing various professions related to and unrelated to the construction sector.

Spontaneous volunteers undertake activities without full coordination, making it difficult to match them with appropriate tasks due to the unknown nature of their education and qualifications (Whittaker et al., 2015). In this project, there were instances of inefficient use of skilled labor due to coordination issues, such as a carpenter performing roofing tasks while a roofer engaged in carpentry. Another incident experienced personally by the researcher involved inexperienced volunteers, including the researcher, learning three different approaches to marble work from three more experienced volunteers, resulting in material wastage and ultimately leading them to abandon the task and switch to another job. Consequently, various inefficiencies emerged, including wasted labor time, teaching time for skilled individuals, and material wastage.

Among spontaneous volunteers, some individuals lacking training and coordination may disrupt the organization's operations, have adverse effects, and lead to resource wastage. Interference by spontaneous volunteers in the way tasks are carried out has resulted in a decline in volunteer motivation (Whittaker et al., 2015; Yükseler & Yazgan, 2022). For example, during the painting process, a volunteer without experience in the construction sector cautioned a professional painter, suggesting they were performing the task incorrectly. Similar dialogues between experienced and inexperienced volunteers were observed throughout the project, leading to a decline in motivation among experienced volunteers and subsequently causing resource wastage.

Lack of organization and information among spontaneous volunteers regarding emergencies and disasters creates challenges and risks such as safety issues (Yükseler & Yazgan, 2022). Fieldwork was conducted without adequate safety measures to deliver temporary housing to earthquake victims as quickly as possible, resulting in some volunteers experiencing work-related accidents. For example, a volunteer injured their hand while using a wood-cutting machine without safety apparatus.

Spontaneous volunteers may participate in activities for short or long durations. In short-term participation, lack of continuity can lead to wastage (Yükseler & Yazgan, 2022). In this project, individuals from professions unrelated to construction were taught tasks, resulting in additional time loss, task repetition, safety concerns, and material wastage. For instance, a volunteer with no prior experience in wood cutting performed the task, leading to time and resource wastage during the learning process. However, this situation evolved into a significant learning environment as volunteers who learned the task continued their participation, addressing the labor shortage and ensuring project continuity. A volunteer who learned wood cutting from a professional later expedited the completion of the task by sharing their experiences with other volunteers. While short-term volunteers could not transfer their acquired skills, the transfer of learned experiences facilitated workforce support. This highlights the importance of continuity in volunteer participation.

Time is a crucial dimension in volunteering (Wilson & Musick, 1997). In this project, transportation to the production site consumed a significant amount of volunteers' time, with public transportation taking nearly three times longer than personal vehicles. To address this issue, volunteers spontaneously organized to use their own vehicles as shuttles, increasing participation.

Typically, humanitarian efforts are orchestrated through formal organizations which solicit aid (Snyder & Omoto, 2008). However, in this project, the initiators are also spontaneous volunteers. Therefore, many stakeholders came together to ensure the project's realization. The project initiators spearheaded the management of stakeholders. Given the project's abrupt inception amidst an emergency scenario, its management followed an improvisational paradigm. While this approach yielded manifold advantages, it also engendered certain adverse repercussions. For instance, resources were needed for the library involved in the project, and simultaneously, another volunteer group expressing their desire to set up a library in the earthquake-stricken area was actively searching for a location via social media. Consequently, these two teams converged at a common location to address their mutual needs. The researcher had the opportunity to observe the process by participating in both teams. According to the established plan, a date was set for the installation. However, due to the limited number of individuals trying to manage multiple tasks, poor time management, and ineffective communication, it was discovered upon arrival at the earthquake-stricken area on the designated date for library installation that the construction of the structure where the installation was to take place had not been completed. With only two days remaining to complete the library project, volunteers from the area and earthquake victims were enlisted to finish the remaining construction tasks swiftly. The library installation was eventually accomplished. Consequently, despite the challenges in time, resource, and communication management associated with the "make it up as you go" management style, opportunities arose to enhance the project through rapid decision-making, problem-solving, and stakeholder collaborations.

Discussion

This research is centered on a project aimed at constructing temporary structures for earthquake survivors. The primary rationale for selecting this project as a case study lies in the remarkable collaborative effort exhibited by approximately 4000 volunteers from diverse professional backgrounds. While this collective endeavor yielded community benefits, the study endeavors to underscore areas warranting attention in future initiatives. To this end, this research employs a participatory research approach to identify and elucidate potential areas for improvement within the project.

Understanding the role of spontaneous volunteers in the production of much-needed shelter areas in unexpected situations necessitates understanding the work environment, interpersonal relationships, project management team, and work practices. Although each observation is unique and non-repeatable, patterns have been identified due to the observations, and this patterned information has been noted and recorded. While access to the observation area is often challenging in participant observer research methods (Iacono et al., 2009), in this project based on volunteering, participation in and access to the work environment have been relatively easy. The aim is to uncover implicit information with participant observation and to improve the process with measures to be taken in future studies. The participant observer method is criticized because the researcher is not an independent observer but a participant, as it is thought that the researcher will conduct the research with emotional rather than objective approaches (Iacono et al., 2009). However, it is incumbent upon the researcher to establish a rapport founded on trust, and objectively collect, analyze, and present empirical evidence (Iacono et al., 2009). Despite the propensity to receive positive appraisals owing to the altruistic nature of the project, this study has embraced an objective stance, cognizant of the broader context, aiming to preemptively address analogous challenges in future endeavors while remaining steadfastly committed to transparent and unbiased data presentation.

Social media is increasingly utilized during major disasters as a communication tool (Meier, 2013). The growing accessibility of communication technologies such as social media facilitates increased volunteer participation in emergencies and disasters (Whittaker et al., 2015). Previous studies have successfully utilized real-time social media data to aid disaster recovery and humanitarian efforts (Meier, 2013). For instance, in the aftermath of Hurricane Sandy in 2012, a "digital haystack" comprising half a million Instagram photos and 20 million tweets was generated within just a few days to aid in the recovery of lost items (Meier, 2013). Similarly, following the 2010 Haiti earthquake, a crisis map was initiated within hours using data from social media, identifying urgent needs and expediting relief efforts with the help of volunteers worldwide (Whittaker et al., 2015). Following the earthquakes on February 6, calls for help on social media were matched with maps by programmers to accelerate rescue efforts for those trapped under rubble. This research demonstrates the power of social media in reaching volunteers and collaborating with stakeholders to address the shelter needs of earthquake survivors.

Volunteer activities play a central role in strengthening human-government relations (UNV, 2021). In this project, shelters for earthquake survivors were constructed in collaboration with the government. Such volunteer initiatives encourage better management practices and prompt authorities to take action (Whittaker et al., 2015). Through communication and collaboration with government officials, volunteers and the government mobilized to meet the housing needs of 100 families.

Volunteers from various professions, both related and unrelated to construction, quickly collaborated in this project, creating an environment conducive to learning and teaching. This learning environment has transformed into a learning environment that foster consensus-building, strengthens professional knowledge, and allows for the sharing of perspectives (Chou & Wu, 2014). Observations supported by the literature were conducted in this project learning environment. Volunteers contributed to the project and acquired personal skills through their learning experiences in this environment. Additionally, in this study, it is evident that participants' long-term involvement in the project, rather than short-term participation, could reduce potential inefficiencies by maximizing the transfer of their experiences, highlighting the importance of sustained volunteer engagement.

Spontaneous volunteers contribute with adaptability, innovativeness, collaborative spirit, and responsiveness during disaster processes. Volunteers need to allocate time for their participation in activities (Whittaker et al., 2015). Due to the distance of the project location and transportation difficulties, there were hesitant volunteers. However, collaboration among volunteers in the project resolved transportation issues and increased time and participation. Previous studies also indicate that cooperative behavior, collaboration, and mutual assistance enhance social capital (Imperiale & Vanclay, 2016). This study underscores the effectiveness of spontaneous volunteers' organizational abilities, supporting previous research.

Previous research has emphasized the inevitability of volunteer participation during disaster processes and the importance of community management (Whittaker et al., 2015). In this study, uncertainties in project management, unclear job descriptions, coordination and communication problems have led to various inefficiencies such as task repetition, occupational safety issues, talent, time, and cost wastage. Effective project management is crucial in eliminating these problems. Ensuring the integrity and timeliness of information transfer and effective communication are necessary for coordination during disaster processes (Chou & Wu, 2014). Furthermore, although no accidents resulting in permanent damage were identified based on the researcher's findings from the project work, more emphasis should be placed on safety measures in future studies. Effective communication and coordination can leverage spontaneous volunteers’ knowledge, skills, resources, networks, and enthusiasm, mitigate potential risks, and ensure efficient resource utilization.

The improvisational perspective adopted in the project has resulted in negative and positive outcomes. The project managers aimed to build 100 houses within one month. However, due to various disruptions such as volunteer unskilledness and inadequacy, lack of effective project management, prolongation of the process due to government relations, communication problems, the houses were sent to Hatay after 2.5 months. The delay in the process led to a chain reaction, affecting other plans. However, quick decisions were made due to spontaneous actions, and this project initiated after the disaster rapidly connected with other stakeholders, enabling earthquake survivors to access the living spaces they needed.

Collecting, analyzing, and understanding information from past experiences is crucial to strengthen communities' ability to respond positively to unexpected situations and develop defence mechanisms against future hazards (Imperiale & Vanclay, 2016). Therefore, this study’s positive and negative implications contribute to future research, providing data that promote community resilience.

Conclusion

This research examines the impact of spontaneous volunteers on community resilience during disaster scenarios. Focused on a volunteer-led project addressing the shelter needs of earthquake victims following the February 6 earthquake, the research observes a unique collaboration involving approximately 4000 volunteers, regardless of their dependency or independence, and their affiliation with the construction industry. Employing the participant observer research method, the study reveals both the opportunities and challenges presented by spontaneous volunteers through a synthesis of field data and literature research.

The study underscores the pivotal role of social media in facilitating rapid interaction among participants, stakeholders, and governmental bodies. It emphasizes the importance of understanding and strengthening the self-organizing capabilities of spontaneous volunteers, alongside the resilient social processes they engender. Long-term volunteer engagement emerges as crucial for project completion, highlighting the significance of continuity. Moreover, creating a conducive learning environment, fostering consensus-building, knowledge enhancement, and perspective-sharing among volunteers, enhances their contributions and personal growth.

Leveraging community capacities and refining lessons learned are imperative to bolster community resilience during disasters. While acknowledging the tangible benefits of collective volunteer efforts, the study identifies potential areas for project enhancement, such as addressing training gaps and improving coordination and communication. Effective volunteer management is essential to mitigate risks associated with volunteer actions.

The study's findings align with existing literature, offering a foundation for future research endeavors. Using insights from this study, future studies can develop robust strategies and interventions to bolster community resilience and fortify disaster preparedness efforts.

References

AFAD (Disaster and Emergency Management Authority). (2023). *06 February 2023 Pazarcık-Elbistan Kahramanmaraş (Mw: 7.7 – Mw: 7.6) Earthquakes Report*. Retrieved March 3, 2023, from https://deprem.afad.gov.tr/assets/pdf/Kahramanmara%C5%9F%20Depremi%20%20Raporu_02.06.2023.pdf

Alexander, D. E. (2013). Resilience and disaster risk reduction: an etymological journey. *Natural hazards and earth system sciences*, 13(11), 2707-2716.

Anthony, K. H. (1987). Private reactions to public criticism; students, faculty, and practicing architects state their views on design juries in architectural education. *Journal of Architectural Education*, 40(3), 2-11.

Arslan, H. (2007). Re-design, re-use and recycle of temporary houses. *Building and Environment*, 42(1), 400-406.

Cambridge Online Dictionary. Retrieved February 28, 2024, from https://dictionary.cambridge.org/tr/

Chen, D., Wang, G., & Chen, G. (2021). Lego architecture: Research on a temporary building design method for post-disaster emergency. *Frontiers of Architectural Research*, 10(4), 758-770.

Chen, S., Zhang, Z., Yang, J., Wang, J., Zhai, X., Bärnighausen, T., & Wang, C. (2020). Fangcang shelter hospitals: a novel concept for responding to public health emergencies. *The Lancet*, 395(10232), 1305-1314.

Chou, J. S., & Wu, J. H. (2014). Success factors of enhanced disaster resilience in urban community. *Natural Hazards*, 74, 661-686.

Finsterwalder, J., Chen, N. C., Hall, C. M., Prayag, G., & Tombs, A. (2024). Transformative places and the citizenship experience: A dynamic perspective of disasters, transitional servicescapes, and place attachment. *Journal of Retailing and Consumer Services*, 77, 103628.

Garmezy, N., & Masten, A. S. (1986). Stress, competence, and resilience: Common frontiers for therapist and psychopathologist. *Behavior Therapy*, 17(5), 500-521.

Graveline, M. H., & Germain, D. (2022). Disaster risk resilience: Conceptual evolution, key issues, and opportunities. *International Journal of Disaster Risk Science*, 13(3), 330-341.

Holling, C. S. (1973). Resilience and stability of ecological systems. *Annual Review of Ecology and systematics*, 4(1), 1-23.

Imperiale, A. J., & Vanclay, F. (2016). Experiencing local community resilience in action: Learning from post-disaster communities. *Journal of Rural Studies*, 47, 204-219.

Ji, H. (2018). Linking risk reduction and community resilience. *In Oxford Research Encyclopedia of Natural Hazard Science*.

Knight, C. (2007). A resilience framework: Perspectives for educators. *Health Education*, 107(6), 543-555.

Iacono, J., Brown, A., & Holtham, C. (2009). Research methods—A case example of participant observation. *Electronic Journal of Business Research Methods*, 7(1), 39-46.

Masten, A. S., Best, K. M., & Garmezy, N. (1990). Resilience and development: Contributions from the study of children who overcome adversity. *Development and Psychopathology*, 2(4), 425-444.

Mauroner, O., & Heudorfer, A. (2016). Social media in disaster management: How social media impact the work of volunteer groups and aid organisations in disaster preparation and response. *International Journal of Emergency Management*, 12(2), 196-217.

Meier, P. (2013). Human computation for disaster response. *In Handbook of human computation* (pp. 95-104). New York, NY: Springer New York.

Merriam-Webster Online Dictionary. Retrieved February 28, 2024, from https://www.merriam-webster.com/

Myers, M. D., & Avison, D. (Eds.). (2002). *Qualitative research in information systems: a reader*. Sage.

Online Etymology Dictionary. Retrieved February 28, 2024, from https://www.etymonline.com/

Penner, L. A. (2004). Volunteerism and social problems: Making things better or worse?. *Journal of Social issues*, 60(3), 645-666.

Rock, P., & Rock, P. (1979). Participant observation. *The making of symbolic interactionism*, 178-216.

Snyder, M., & Omoto, A. M. (2008). Volunteerism: Social issues perspectives and social policy implications. *Social Issues and Policy Review*, 2(1), 1-36.

Timmerman, P. V. (1981). Resilience and the collapse of society: A review of models and possible climatic applications. *Toronto: Institute for Environmental Studies*, University of Toronto.

United Nations Volunteers (UNV) programme. *2022 State of the World's Volunteerism Report. Building equal and inclusive societies.* Bonn; 2021. Available from: https://swvr2022.unv.org/

Whittaker, J., McLennan, B., & Handmer, J. (2015). A review of informal volunteerism in emergencies and disasters: Definition, opportunities and challenges. *International Journal of Disaster Risk Reduction*, 13, 358-368.

Wilson, J. (2000). Volunteering. *Annual Review of Sociology*, 26(1), 215-240.

Wilson, J., & Musick, M. (1997). Who cares? Toward an integrated theory of volunteer work. *American Sociological Review*, 694-713.

Windle, G. (2011). What is resilience? A review and concept analysis. *Reviews in Clinical Gerontology*, 21(2), 152-169.

Yükseler, M., & Yazgan, J. (2022). Spontaneous Volunteers in Emergencies and Disasters. *In Natural Hazards-New Insights*. IntechOpen.

Evaluation of Possible Post-Earthquake Resilience of Balıkesir-Gömeç District

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Abstract

Earthquake resilience is the capacity of a region to be prepared, durable and recoverable against earthquake hazards. Gömeç – Balıkesir area is chosen as a reference city that would represent small scale young cites that are poorly planned, that has infrastructure deficiencies and has very dense seasonal population with very limited economic redundancy. The recovery ability of the city, which can be defined as the city's ability to perform its vital functions again after a disaster, will be examined on the basis of internationally recognized "resilient city parameters". As a result of the study, Gömeç "city resilience index" evaluation results will be compared with some international cities. Results will be discussed in terms of resilient city requirements. Beyond physical preparations, what needs to be done to provide post-earthquake psychological, economic and social support, and to increase public awareness and participation will be discussed based on city resilience index results.

Keywords: *earthquake risk, resilient city, disaster preparedness*

Introduction

When considered in the context of urban planning, resilience entails not only creating durability through engineering methods against potential adversities such as earthquakes, terrorist attacks, climate change, and other disasters but also encompasses a wide array of complex issues and topics like poverty, crime, women, youth, and migration. Urban resilience, fundamentally, refers to a city's ability to attain acceptable functionality and equilibrium in the face of unexpected impacts and extraordinary circumstances. It involves returning to a state of recovery as quickly as possible and, more importantly, ensuring that the changes and transformations occurring are comprehensible and adaptable to both the individuals shaping the city and its administration. While having a robust and enduring structure is crucial, it's not the essence of resilience but rather a significant component of its integrity. (Tüysüz, 2024)

When urban resilience is set as a challenging yet realistic goal, it encompasses expectations that can be defined as prerequisites: durability, flexibility, redundancy, rapid recoverability, effective communication, strong and capable governance, a sense of duty ingrained in individuals, both physically and mentally resilient. Within the scope of this study, the recovery capacity of Gömeç district in the event of a potential earthquake disaster, defined as its ability to restore vital functions, will be examined based on resilient city parameters. In this context, the preparatory main parameters of the city will be outlined, considering the scenario that will unfold post-disaster.

Gömeç Case Study – Field Study Results and Disaster Plan Report Review

The data used in this study was produced within the scope of Mimar Sinan Fine Arts University, Institute of Science, Department of City and Regional Planning, Urban Conservation and Renewal Master's Program, Workshop course. Course outcome reports and posters were created by graduate students Anıl Tüysüz, Ghadeer Al-Shamiri, Thais Melz and Züleyha Uğurçay. Workshop facilitators who contributed to the studies were Prof.Dr. M. Rıfat Akbulut, Assoc.Prof.Dr. Dilek Erbey, Assoc.Prof.Dr. Sibel Gürses Söğüt, Research Assistant Özlem Çalışkan. The field studies carried out in Gömeç in October 2023 focused on an area of approximately 25 hectares in the central neighborhood of Gömeç's Kemalpaşa District.

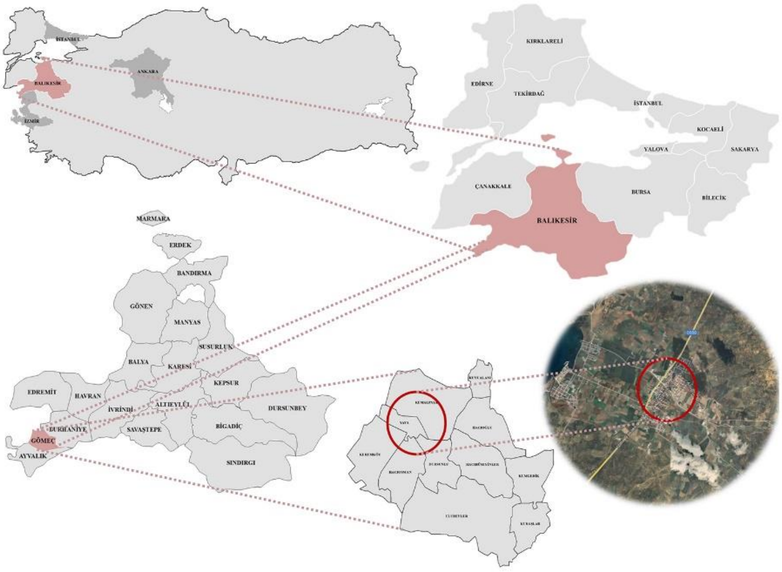


Figure 1: Location of Gömeç (Mimar Sinan Güzel Sanatlar Üniversitesi, 2023-2024).

Gömeç is the smallest district in Balıkesir Province, situated within the Marmara Region, one of the seven geographical regions of our country. It spans an area of 178.5 km² and has a population of 16,880 according to the 2022 TÜİK data. (TÜİK, 2024) The district center sits at an elevation of 10 meters above sea level.

Urban Form and Land Use;

At the upper scale, urban form affects many subsystems of the city, such as the direction of development of the city, transportation and infrastructure systems, and distribution of land use. The fringing or compactness of the city form creates different types of effects in terms of earthquakes and other disasters. (Peker & Orhan, 2021)

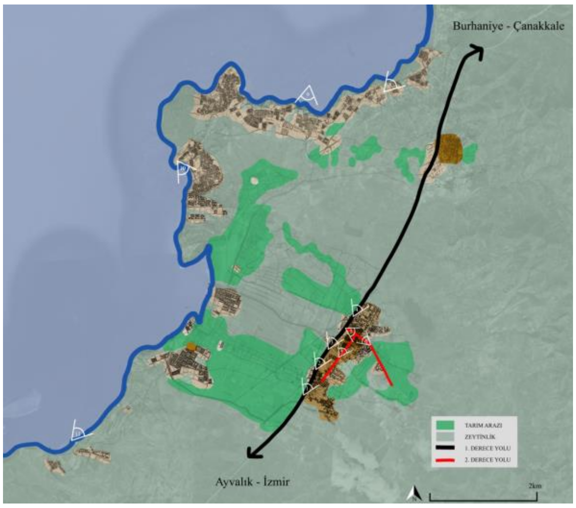


Figure 2: Macroform of Gömeç (Mimar Sinan Güzel Sanatlar Üniversitesi, 2023-2024).

Gömeç is a settlement located to the east of the highway leading to Bursa and Izmir, in the section between Ayvalık and Burhaniye and near the Edremit Bay. Gömeç's growth took place especially while following the highway. In the last fifty years, new constructions have emerged and spread along the coast. In the current situation, the general layout of the city is dense and compact in the center, while multiple and scattered new residential areas stand out in the coastal area. (Mimar Sinan Güzel Sanatlar Üniversitesi, 2023-2024)

While Gömeç district's rural character and its consequent low-density development present an advantage, the increase in density in the center, as seen in many cities, leads to an increase in building density and height. This, in turn, increases the likelihood of it becoming the most affected area in the event of a possible earthquake. The increase in density poses a problem in creating necessary open spaces and gathering areas in this region.

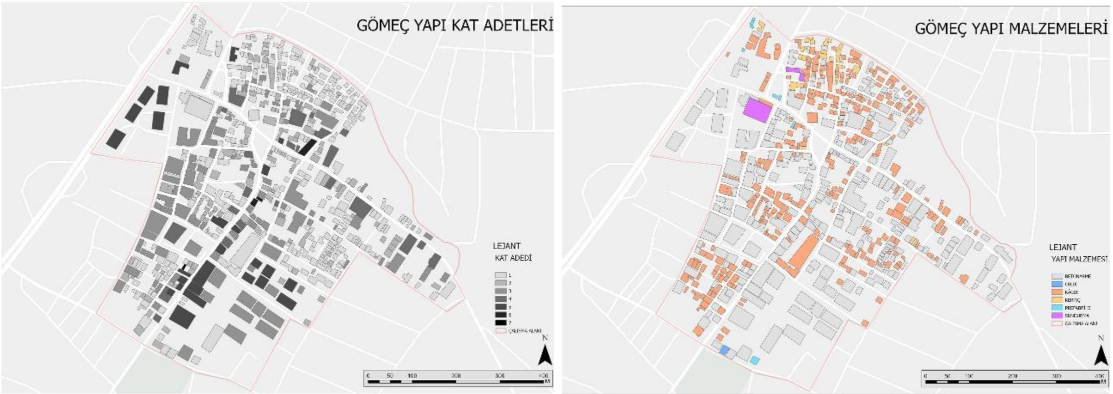
City Management and Planning Strategy;

By examining the planning history of Gömeç District from past to present, the impact of plan decisions on the development of the physical space of the city and its social and economic structure was examined. In line with the plan decisions taken, it has been determined that the city is envisaged to grow both in the eastern axis in the center and in the western axis towards the coast.

In the planning process from past to present, plan decisions based on tourism-oriented development were mostly produced, and agricultural areas were opened to development; It has been observed that agricultural activities, especially olive cultivation, which has an important place in the city's economy, do not have sufficient importance in plan decisions. (Mimar Sinan Güzel Sanatlar Üniversitesi, 2023-2024)

Spatial Analyses;

The height of the working area is between 1 and 7 floors, and the majority are 1 and 3 floors. These buildings have mainly commercial and residential functions. Some of them are used as public buildings, government offices, police offices, mufti offices, mosques and warehouses. Typologically, the ground floor is used for commerce and it has been determined that the buildings generally contain between 1 and 4 different commercial functions. The other floors are used as residences. (Mimar Sinan Güzel Sanatlar Üniversitesi, 2023-2024)



*a *b

Figure 3: a) Building floors, b) Construction materials (Mimar Sinan Güzel Sanatlar Üniversitesi, 2023-2024).

Seismicity of Gömeç;

According to the Turkey Earthquake Hazard Map, Gömeç is situated in areas designated as 'High Hazard.' The active faults that pose a threat to Gömeç and its immediate vicinity are the branches of the North Anatolian Fault Line within the Marmara Sea, which have the potential to impact the entire Marmara region. Gömeç is in close proximity to these faults.

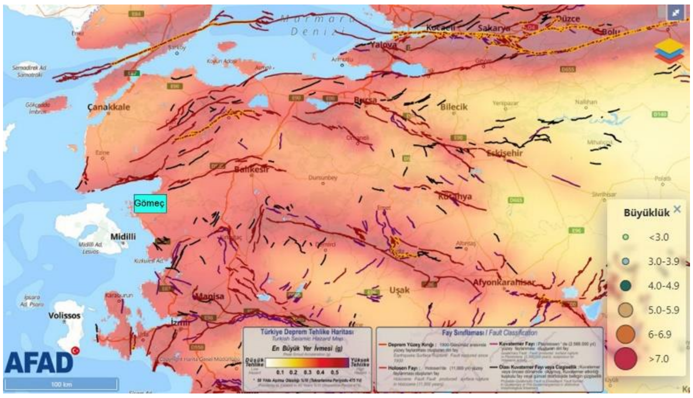


Figure 4: Türkiye Earthquake Hazard Map (AFAD, 2024).

According to the Disaster Plan Report (Gömeç Kaymakamlığı, 2013); 33 significant earthquakes were recorded in the district from 1845 to 1970; 8 of them were of the 4th degree, 6 of them were of the 5th degree, 16 of them were of the 6th degree, 2 of them were of the 7th degree and 1 of them was of the 10th degree. The district is a depression area with an alluvial soil structure, between the Dikili-Ayvalık coasts and the coasts of Lesbos Island, in the Gulf of Edremit, in the Northwest-Southeast direction. Heavy, medium and light damage to the houses that may be affected by an earthquake of magnitude 7 with magnitude X is predicted as in the Table-1 below.

Using this table, heavy, medium and light building damage in earthquakes with magnitudes between VI and X was calculated by dividing the number of houses in the district, and the result is shown in the table below. (Buildings in summer sites and cooperatives have also been added to the table.) (Gömeç Kaymakamlığı, 2013)

Table 1. Expected housing damage rates.

Intensity	Heavy Damage (%)	Medium Damage (%)	Light Damage (%)
VI	0,04	0,22	0,24
VII	0,91	2,67	2,59
VIII	2,82	4,41	5,31
IX	15,70	18,16	22,75
X	33,06	15,29	19,14

Table 2. Total number of damaged houses.

District's Name	Heavy Damage	Medium Damage	Light Damage
GÖMEÇ	2479	1147	1436

Transportation Systems;

According to the disaster report; Considering that the road would be unusable as a result of possible breaks on the E-87 Highway passing near the district, alternative routes were determined. It is envisaged that rescue teams and aid from outside will be provided from Tuzla airstrip (air transportation) and from Ayvalık-Burhaniye Piers (sea transportation vehicles). (Gömeç Kaymakamlığı, 2013)

Technical Infrastructure;

Water Network: The total length of the water network of the district center is approximately 137 km. and the average flow rate of flowing water is stated as 105 lt/sec.

District's drinking water facilities:
1.Burhaniye Çoruk Village Water Wells (Gömeç): L1, L2, L3, L4 wells
2.Gömeç Water Tank (1500 tons)
3. Burhaniye Çoruk Village Water Wells (Karaağaç): Old, New Well
4.Karaağaç Town Water Tank (1200 tons)
5.Karaağaç Town Çamlık Side Artesian Park

Sewerage Network: It has been stated that the sewerage network in the district center has been completed and put into service.

Electricity and Communications Network: The number, type and location of the transformers owned by the district are given in detail in the disaster report. It is stated that there is 1 generator in Gömeç District Hospital as a backup power source in case of power outage.

According to the report (Gömeç Kaymakamlığı, 2013); It is accepted that after a magnitude VII and magnitude IX earthquake that may occur in the district, 25% of the existing electricity and telephone lines will be damaged, and there will be 15 breaks in drinking water lines for every 100 km in length.

Population Status;

According to 2023 TÜİK data, the population of Gömeç District is 17556 people. (TÜİK, 2024) It is noteworthy that the district population has increased more rapidly in recent years. (Figure 5) It is thought that this is due to the return to Anatolia from metropolitan cities after the pandemic experienced in 2021 around the world. (Mimar Sinan Güzel Sanatlar Üniversitesi, 2023-2024)

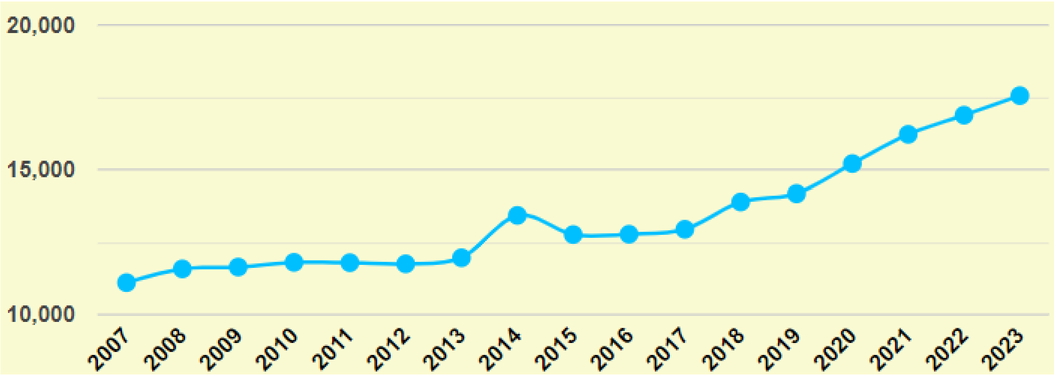


Figure 5: Population chart by years (TÜİK, 2024).

Health Units;

According to the disaster plan report, there is 1 hospital, 2 health posts, 6 Family Health Centers and 1 112 Emergency Health Services Station in the district. (Gömeç Kaymakamlığı, 2013)

Security Organizations;

According to the disaster plan report, there is 1 Police Department organization in the district center within the district borders. (Gömeç Kaymakamlığı, 2013)

Evaluation of Pre-Earthquake City Resilience and Index Parameters

The City Resilience Index is a comprehensive tool designed to help cities assess and strengthen their ability to bounce back from various challenges they may face. These challenges include rapid urbanization, climate change impacts, terrorism threats, and natural disasters. At its core, the index provides a detailed analysis of a city's resilience capabilities. It helps city leaders and planners identify areas where the city is doing well in terms of resilience and areas that require improvement. This diagnostic capability is crucial for cities to understand their strengths and weaknesses and prioritize actions for enhancing resilience.

Moreover, the index is not a static assessment but rather a dynamic tool that tracks changes in resilience factors over time. This longitudinal approach allows cities to monitor their progress and adapt their strategies accordingly.

These dimensions collectively form the bedrock of urban resilience, providing a comprehensive approach to sustaining and enhancing the vitality of cities in the face of adversity. Underpinned by a suite of 12 Goals, these dimensions act as global milestones for cities to aspire to, steering them amidst a spectrum of enduring challenges and abrupt crises. (City Resilience Index, 2024) While universally applicable, the relevance and execution of these goals will differ, mirroring the unique essence and requisites of each city. The 12 goals which consists of 3 goals per fundemantal dimensions are given below in Figure-6.

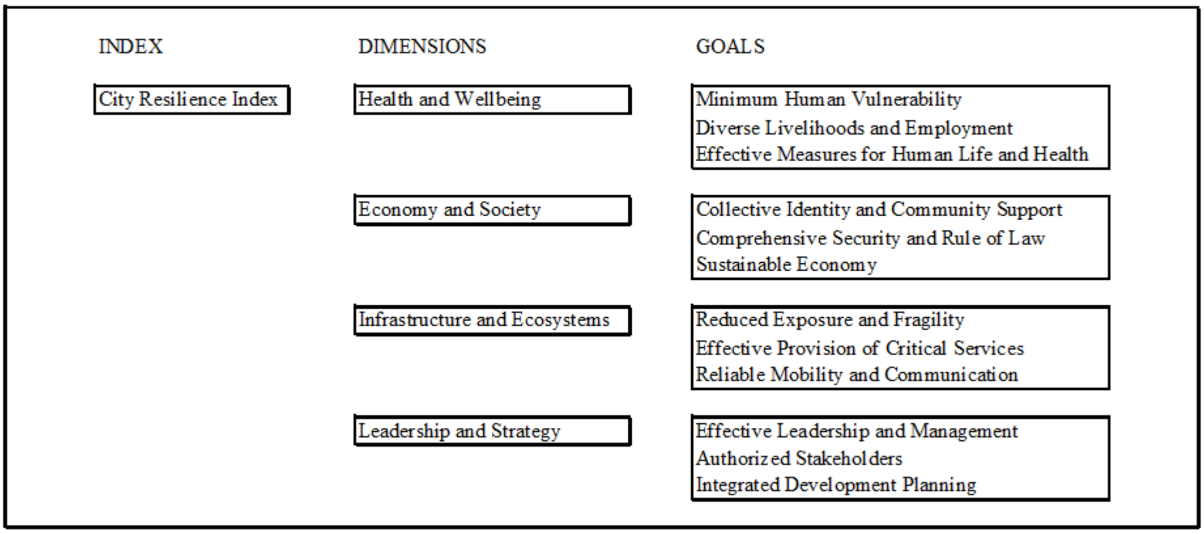


Figure 6: Index dimensions and goals (City Resilience Index, 2024).

The index has been developed by experienced consultants with global expertise and is backed by support from prominent financial institutions and foundations. As a result, it serves as a valuable resource for various stakeholders, including governments, donors, investors, policymakers, and the private sector. These stakeholders can use the index to inform their decisions and develop effective strategies for building resilient urban environments that can withstand and recover from various challenges.

Gömeç Case Study - Desk Study

Based on available framework of city resilience index the case study for Gömeç included most necessary desktop documentation required to convert available data into a comparable index resultant number. Although the city resilience index is not a system to numerically compare possible alternative cities, it is an elegant tool to see deficiencies and to compare documented data with the available data of others based on experienced parameters and indicators of the well established index system, main dimensions and goals of the system framework.

We may expect to see 100% resilience at perfect systems and some lower percentage in real systems. Study considers 20% resilience as a minimum limit for low resilient cities (lower values are not considered) where 40% is considered as the upper limit. Above 40% and lower 60% can be considered as median resilience. Above 60% and lower 80% can be considered as higher resilience and above this limit can be very high resilience cities.

The basis of framework followed by desk study and concluded with following resilience expectations based on 12 main goals of the system. Results are presented in Figure-7 and it can be followed that most goals are seriously below median expectations where some goals are in the median expectations zone. No verified goal had values exceeding the limit and satisfying the requirement for high resilience zone.

Minimum Human Vulnerability	42%
Diverse Livelihoods and Employment	30%
Effective Measures for Human Life and Health	43%
Collective Identity and Community Support	45%
Comprehensive Security and Rule of Law	53%
Sustainable Economy	32%
Reduced Exposure and Fragility	23%
Effective Provision of Critical Services	28%
Reliable Mobility and Communication	45%
Effective Leadership and Management	44%
Authorized Stakeholders	60%
Integrated Development Planning	35%

Figure 7: Distribution of expected resilience percentages to 12 main goals of index.

The collaborated results of the main 12 goals summarized to 4 main dimensions are also prepared to compare and analyze results. Results are presented in Figure-8 and it can be concluded that followed that 2 of the main dimensions are slightly below median expectations where 2 others are just above the limit. Final summarized value is given in Figure-9.

Health and Wellbeing	38%
Economy and Society	43%
Infrastructure and Ecosystems	32%
Leadership and Strategy	46%

Figure 8: Distribution of expected resilience percentages to 4 main dimensions of index.

City Resilience Index	40%

Figure 9: Final index combined from all dimensions and goals.

Conclusion

The data obtained within this study were derived from fieldwork (Mimar Sinan Güzel Sanatlar Üniversitesi, 2023-2024) conducted in the Gömeç district, the official disaster plan report (Gömeç Kaymakamlığı, 2013) prepared for Gömeç, plans and plan notes obtained from the municipality, and discussions with municipal employees. These data, which reveal the current situation of the district, have been evaluated based on internationally recognized "resilient city parameters," leading to the conclusion that the district lacks sufficient resilience. Given that Gömeç is still undergoing urbanization processes, it is important to develop a comprehensive planning approach sensitive to the "resilient city parameters" for the district. Therefore, the city administration should reconsider and develop strategies for each sub-theme at four conceptual scales, as outlined in this study.

Comparison of results contained in the study although is not the purpose of the indexing system is given in Figure-10. It would be targeted to consider results in city resilience index system as main goals and to concentrate on each to reach to a more resilient city before a serious earthquake or similar disaster hits the city. Each possible disaster may be considered to see possible flaw points and may be targeted to fulfill requirements.

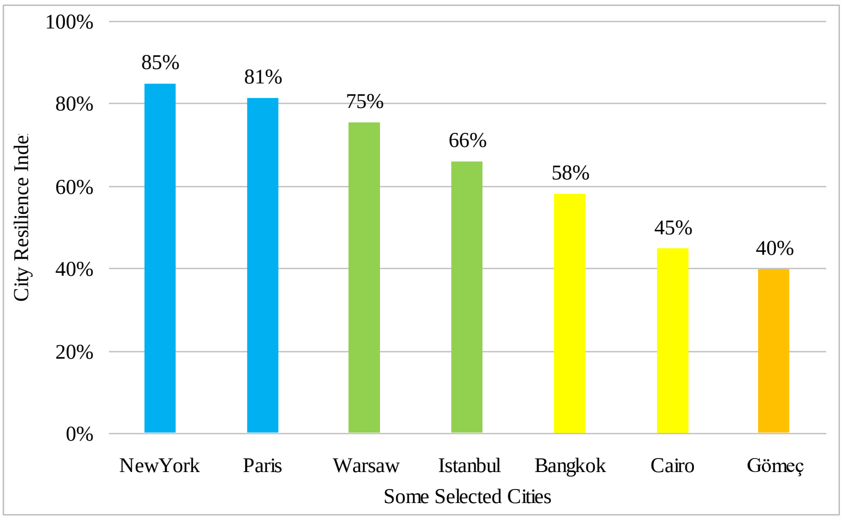


Figure 10: Comparison of city resilience final index scores of some cities.

References

AFAD. (2024). *Deprem Kataloğu*. deprem.afad.gov.tr: https://deprem.afad.gov.tr/event-catalog

City Resilience Index, The Rockefeller Foundation, Arup. (2024). *City Resilience Index*. www.cityresilienceindex.org: https://www.cityresilienceindex.org/#/

Gömeç Kaymakamlığı. (2013). *Gömeç İlçesi Afet Planı.*

Mimar Sinan Güzel Sanatlar Üniversitesi. (2023-2024). *Gömeç Raporu.* MSGSÜ Kentsel Koruma ve Yenileme YL Programı-KNK503 Kentsel Koruma ve Yenileme Atölyesi-1, İstanbul.

Peker, E., & Orhan, E. (2021). Mekânsal Planlamada Deprem Riski ve İklim Krizini Birlikte Ele Almak. *Planlama*, 7(5), 288-301.

TÜİK. (2024). *Türkiye Nüfusu İl ilçe Mahalle Köy Nüfusları*. https://www.nufusune.com/gomec-ilce-nufusu-balikesir

Tüysüz, A. (2024). Dayanıklılık mı? Dirençlilik mi? Hangisi Daha "Resilience"? *Spektrum*, 7-11.

Preparation City Resilience Rating after Earthquakes with Target Performance Parameters

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Abstract

Multi-disciplinary nature of urban design and conservation in urban planning when comes together with the earthquake hazard preparedness and disaster management, especially after earthquake disasters, makes a very complex environment that requires a very careful language between various sciences. Different sciences such as human, economy, public management, engineering, earth will all have to communicate for a resilient city. Strong communication is necessary for complex problem solving. Every discipline should translate the expected performance to their own language and satisfy requirements. Naturally rising conflicts should be solved based on disaster management and urban design requirements. The large magnitude 2023 earthquake in Turkey, affected millions of people and tens of large cities. As almost a year has passed after the disaster it is now more possible to differentiate between the cities as some has shown stronger resilience and some has shown poorer. This study will underline importance of some performance parameters to rate cities for post-earthquake resilience based on three large size cities Antakya, Kahramanmaraş and Adıyaman cities that are heavily affected by the earthquake. The mentioned parameters will be identified and there cities will be discussed based on these parameters. Effect of these parameters on observed resilience after the earthquake will be discussed.

Keywords: *resilient city, disaster preparedness, earthquake*

Introduction

City resilience encapsulates a city's ability to maintain essential functions and enable its inhabitants, especially those most vulnerable, to persist and prosper despite various adversities. Originating from ecology in the 1970s, resilience describes a system's capacity to sustain or swiftly regain functionality amid disruptions. This concept is pertinent to cities as they are intricate, ever-evolving systems. A city's resilience gains significance when it faces potential widespread upheaval due to persistent strains or abrupt calamities, threatening the integrity of both physical and societal structures.

The visual representation of higher city resilience in both these observation axes “physical impact” and “social impact” that form an observation plane together with the third axis “economic impact” to form an observation space is given below as directly taken from (City Resilience Index, 2014) original document.

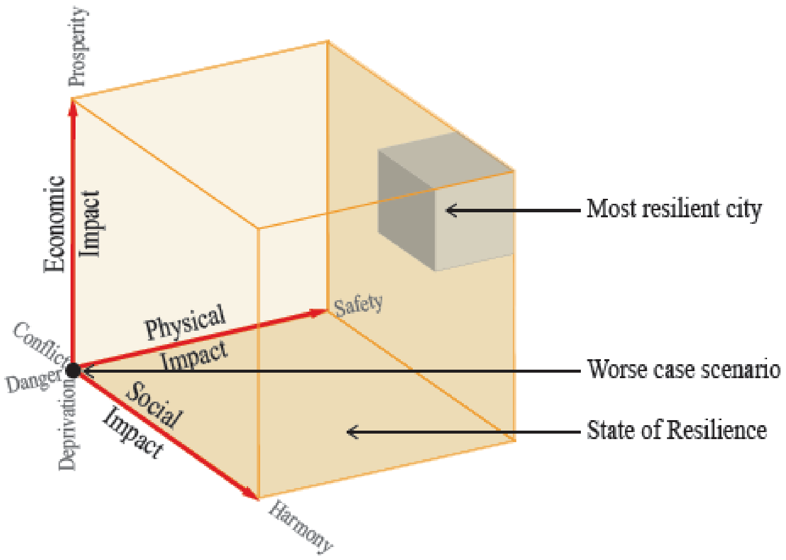

Figure 1: Relationship of the 3 selected dimensions to the types of impacts in a city. (City Resilience Index, 2014).

However, the traditional notion of resilience may overlook the intricate power dynamics that influence urban operations and responses to disturbances. In urban settings, resilience has evolved to connect disaster risk reduction with climate change adaptation, shifting from conventional disaster risk management focused on specific hazards. It acknowledges the potential for a broad spectrum of unpredictable disruptive events. The emphasis of resilience lies in bolstering a system's overall performance in the presence of diverse threats, rather than solely aiming to prevent or lessen the impact on assets from incidents. This approach fosters a more comprehensive and adaptable strategy for urban resilience, addressing the multifaceted nature of city systems and the challenges they face.

The Earthquake

The February 2023 Kahramanmaraş earthquakes inflicted profound hardships and uncertainties upon the inhabitants of the affected cities, including Gaziantep, Şanlıurfa, Diyarbakır, Adana, Adıyaman, Osmaniye, Hatay, Kilis, Malatya, and Elazığ. The mainshock and their aftershocks wrought extensive destruction, particularly in Hatay(Antakya), Adıyaman, and Kahramanmaraş.

The calamity is staggering, with the death toll exceeding 60,000, serious injuries surpassing 120,000, and countless individuals displaced from their homes and customary lifestyles. The economic repercussions (T.C. Cumhurbaşkanlığı Strateji ve Bütçe Başkanlığı, 2024) are equally severe, with damages estimated to exceed $160 billion, still not being to account for all secondary economic losses. A year on, pivotal questions about the recovery of Antakya, Kahramanmaraş, and Adıyaman remain unanswered. The extent of their recuperation, the return to pre-disaster activity levels, and the quantitative measurement of the earthquake's impact on the shock and recovery phases are still under scrutiny. Addressing these inquiries necessitates highlighting the significance of certain performance parameters that gauge a city's post-earthquake resilience. These metrics are crucial for understanding the recovery process and for planning future resilience strategies. They serve as benchmarks for evaluating the effectiveness of interventions and the resilience of urban infrastructure and social systems in the wake of such catastrophic events.

City Resilience Index

The City Resilience Index (City Resilience Index) has been meticulously crafted to empower urban areas to systematically assess and enhance their resilience. This is increasingly crucial as cities worldwide confront escalating challenges from rapid urbanization, climate change, terrorism, and a spectrum of natural hazards.

At the heart of the “index” methodology is its diagnostic capability, which allows cities to pinpoint their resilience strengths and areas for improvement. By tracking these factors over time, “index” methodology provides a dynamic and nuanced understanding of a city's resilience journey. Unlike other metrics, the City Resilience Index eschews direct comparisons between cities or an overarching score. Instead, it focuses on tracking progress over time, offering a tailored assessment that reflects each city's unique context.

Developed and documented by globally experienced consultants and backed by leading financial institutions and foundations, this “index” serves as a guidance tool for governments, donors, investors, policymakers, and the private sector to devise robust strategies for nurturing resilient urban environments.

In the aftermath of an earthquake, the “index” methodology considers the broad spectrum of shockwaves felt across both the physical and social fabrics of the city. It is designed to be a versatile tool, accessible not only to city governments but also to universities, NGOs, community groups, and other stakeholders. Importantly, the “index” approach includes mechanisms to incorporate the perspectives of marginalized and vulnerable populations, who often bear the brunt of disruptions and failures disproportionately.

Through its methodological rigor and adaptability, the City Resilience Index stands as a beacon for cities striving to navigate and prosper amidst the uncertainties of the modern world. It offers a shared language for resilience, fostering dialogue and knowledge exchange among urban centers globally. The main framework and its sub packages are shown after being redrawn based on (City Resilience Index - Resources, 2018) in Figure-2.

Leadership & Strategy	Health & Wellbeing
Effective Leadership and Management	**Minimal Human Vulnerability**
1. Appropriate government decision-making	1. Safe & affordable housing
2. Effective co-ordination with other government bodies	2. Adequate affordable energy supply
3. Proactive multi-stakeholder collaboration	3. Inclusive access to safe drinking water
4. Comprehensive hazard monitoring and risk assessment	4. Effective sanitation
5. Comprehensive government emergency management	5. Sufficient affordable food supply
Empowered Stakeholders	**Diverse Livelihoods and Employment**
1. Adequate education for all	1. Inclusive labour policies
2. Widespread community awareness and preparedness	2. Relevant skills and training
3. Effective mechanisms for communities to engage with government	3. Local business development and innovation
	4. Supportive financing mechanisms
	5. Diverse protection of livelihoods following a shock
Integrated Development Plannig	**Effective Safeguards to Human Life and Healty**
1. Comprehensive city monitoring & data management	1. Robust public health systems
2. Consultative planning process	2. Adequate access to quality healthcare
3. Appropriate land use and zoning	3. Emergency medical care
4. Robust planning approval process	4. Effective emergency response services
Infastructure & Ecosystems	**Economy & Society**
Reduced Exposure and Fragility	**Collective Identity and Community Support**
1. Comprehensive hazard and exposure mapping	1. Local community support
2. Appropriate codes, standards and enforcement	2. Cohesive communities
3. Effectively managed protective ecosystems	3. Strong city-wide identity and culture
4. Robust protective infrastructure	4. Actively engaged citizens
Effective Provision of Critical Services	**Comprehensive Security and Rule of Law**
1. Effective stewardship of ecosystems	1. Effective systems to deter crime
2. Flexible infrastructure	2. Proactive corruption prevention
3. Retained spare capacity	3. Competent policing
4. Diligent maintenance & continuity	4. Accessible criminal & civil justice
5. Adequate continuity for critical assets and services	
Reliable Mobility and Communications	**Sustainable Economy**
1. Diverse and affordable transport networks	1. Well-managed public finances
2. Effective transport operation and maintenance	2. Comprehensive business continuity planning
3. Reliable communications technology	3. Diverse economic base
4. Secure technology networks	4. Attractive business environment
	5. Strong integration with regional and global economies

Figure 2: Main framework with dimensions, goals and indicators.

The City Resilience Index is anchored in 4 fundamental dimensions:

- Health and Well-being: This dimension prioritizes the physical and mental health of all city dwellers and workers, ensuring their overall well-being.
- Economy and Society: It encompasses the societal and economic frameworks that foster harmonious living and collective action among urban residents.
- Infrastructure and Environment: This involves both constructed and natural systems that deliver essential services, safeguard, and establish connections among the urban populace.
- Leadership and Strategy: This dimension underscores the importance of knowledgeable, inclusive, cohesive, and cyclical policymaking within urban centers.

These dimensions collectively form the bedrock of urban resilience, providing a comprehensive approach to sustaining and enhancing the vitality of cities in the face of adversity.

These four pivotal dimensions, underpinned by a suite of 12 Goals that act as global milestones for cities to aspire to. These goals are instrumental in steering cities amidst a spectrum of enduring challenges and abrupt crises. It's important to recognize that while these goals are universally applicable, their relevance and execution will differ, mirroring the unique essence and requisites of each city. This bespoke strategy guarantees that resilience efforts are pertinent and efficacious, tailored to the distinct scenarios presented by urban settings worldwide.

The framework as shown in Figure-2 is supported by 52 indicators that further delineate the 12 Goals and identify the key factors that fortify the resilience of urban frameworks.

Evaluation of Post-Earthquake City and Index Modifications

Although it is critical to use rating systems for urban resilience before any major disasters, reevaluating and potentially refining the pre-event criteria for assessing urban resilience post-earthquake or following any major calamity is also essential as such large-scale events often expose previously hidden frailties within urban systems, governance, and community resilience.

Based on this approach a study is planned to visit earthquake damaged cities with 3 monthly intervals starting from immediate after the earthquake and this study targets the use of city resilience parameters and measure city resilience variation by time after the earthquake based on the same parameters. Although it was planned to visit all 10 cities that were heavily affected, by time only 3 cities were kept on the list and selected that could represent all remaining cities and possible scenarios after earthquakes thus the study concentrated on these cities which are Hatay (Antakya), Adıyaman and Kahramanmaraş. The purpose was to reconsider and recalibrate available city resilience parameters from the viewpoint of post-earthquake perspective.

The study considers that it would be vital to reconsider and possibly recalibrate resilience criteria post-earthquake for the following main expectations:

- Emergent Risk Insights; earthquakes often bring to light new or underestimated risks. For instance, they may expose the susceptibility of specific structures or infrastructural elements that were not fully accounted for in initial resilience evaluations.

- Community Dynamics and Resilience; observing how communities react to and adapt after earthquakes sheds light on resilience factors at the grassroots level. This includes aspects like community solidarity, informal support networks, or emergent adaptive strategies that might not have been considered before.
- Assessment of Infrastructure Robustness; analyzing the performance of infrastructural systems during an earthquake can lead to adjustments in resilience criteria. If certain essential services failed unexpectedly or outperformed expectations, such insights could refine our metrics for resilience.
- Understanding Long-Term Impacts; the prolonged effects of earthquakes on urban areas—such as demographic shifts, changes in land use, and economic fluctuations—necessitate a revisited understanding of how cities recover and evolve over time.
- Enhanced Sector Integration; earthquakes underscore the need for cohesive efforts across various sectors to build resilience. It may be necessary to modify criteria to better reflect the synergy between different areas, including infrastructure, healthcare, and social services.

In summary, earthquakes provide a crucial opportunity to deepen our understanding of urban resilience. By revisiting resilience criteria in the aftermath of such events, we can incorporate fresh insights, adapt to changing circumstances, and strengthen our cities against future challenges.

The study focused on key indicators and specifically examined the post-earthquake period. Site visits highlighted various urgent issues at 3 months, 6 months, 9 months, and 12 months after the earthquake. Additionally, comparisons were made between the day of the earthquake and the 3 months preceding it, revealing differences in expectations and effects. The key indicators all together formed a total city resilience index result which changed by time. Following this index change by time is expected to reveal some key parameters and for each city selected. Combined city index values are listed in the Table-1 for each of the evaluations.

Table 1. Resilient city index results of selected cities in specified periods.

	Antakya	Kahramanmaras	Adıyaman
City Resilience Index 3 Months Before	71%	75%	68%
City Resilience Index Event Day	23%	35%	31%
City Resilience Index 3 Months After	29%	53%	45%
City Resilience Index 6 Months After	37%	63%	56%
City Resilience Index 9 Months After	40%	65%	58%
City Resilience Index 12 Months After	42%	66%	60%

Initial assessments, which can be considered as evaluations conducted approximately three months before a significant event, serve as a benchmark. These assessments form the basis for the pre-event city resilience rating system.

On the day of the event, evaluations capture the city’s response. Given the event’s magnitude and the sudden drop in evaluation results, it becomes evident how well-prepared the city and its residents are to withstand the earthquake.

Subsequent evaluations occur at three-month intervals after the event. These results illustrate how the city’s response changes over time. Figure-3 depicts the time-dependent variations in these evaluations, highlighting the significant impact of the event. Notably, the cities under review exhibit varying dynamics, influencing both the response levels and durations

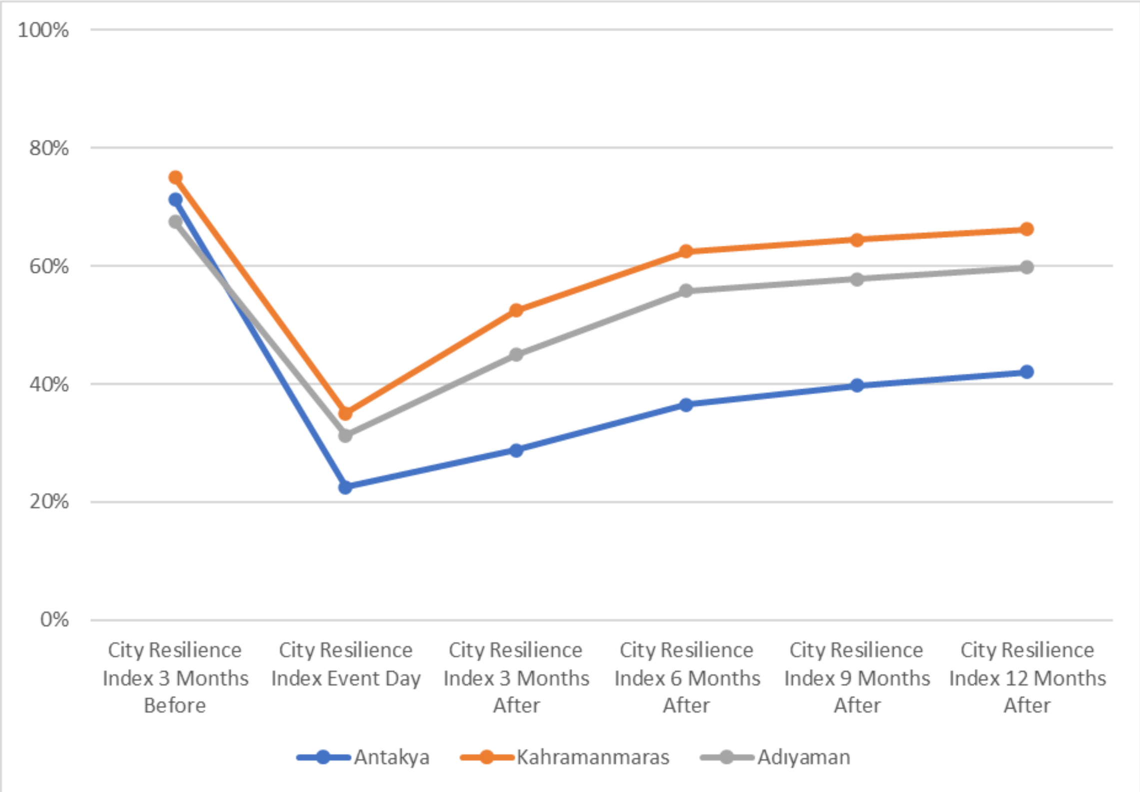

Figure 3: Change in resilience of selected cities over time.

Results and Future Research

The study focused on key indicators and specifically examined the aftermath of an earthquake. Through site visits conducted at intervals of 3 months, 6 months, 9 months, and 12 months after the earthquake, urgent issues were highlighted.

The results shed light on the differences in resilience among cities. While it is crucial to employ rating systems for urban resilience before major disasters, it is equally essential to reevaluate and potentially refine the pre-event criteria for assessing urban resilience post-earthquake or following any significant calamity. Large-scale events often reveal vulnerabilities within urban systems, governance structures, and community resilience that were previously hidden.

The rating system itself is not meant for direct quantitative comparisons between cities or different states of the same city over time. Instead, it serves as a tool to identify challenges and problems. By using the rating system as a comparative tool over time following an extraordinary event, we can track changes in city resilience dimensions and goals. Even the indicators highlighted in reports (City Resilience Index, 2018) play a crucial role in this assessment.
From the study’s perspective, the parameters and indexes established by international organizations can be applied in research across many cities in Turkey—a country prone to

earthquakes. Reference data for cities can serve as a solid foundation for future post-event follow-up efforts.

Analyzing real city responses based on available results allows us to understand the impact of 4 major dimensions and 12 goals on response time and experienced resilience. Furthermore, indicators can be refined to transform available data into a new format based on actual experiences. Similar studies could explore simpler ways to measure these values and conduct data analysis.

Additionally, the earthquake-focused approach discussed here could be broadened to encompass various types of hazards beyond earthquakes.

References

City Resilience Index, The Rockefeller Foundation, ARUP. (2014). *City Resilience Index.* C13-CRI Research Report Vol 1 - Desk Study Report.

City Resilience Index, The Rockefeller Foundation, ARUP. (2018). *City Resilience Index*. www.cityresilienceindex.org: https://www.cityresilienceindex.org/#/

City Resilience Index, The Rockefeller Foundation, ARUP. (2018). *City Resilience Index - Resources.* Retrieved from Explore City Resilience: https://www.cityresilienceindex.org/#/resources

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Impacts of COVID-19 on the Construction Sector

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Abstract

The COVID-19 outbreak, which emerged in Wuhan, China, affected the whole world in a short time and was declared a pandemic by the World Health Organization on March 11, 2020. Due to the COVID-19 pandemic, which has affected the entire world, many sectors such as tourism, hospitality, transportation, international trade, and healthcare have encountered serious problems. The construction sector has also affected the COVID-19 pandemic because it is unsuitable for remote work, problems in material supply, postponed or canceled investment decisions, and economic changes in the world. This study aims to reveal the effects of COVID-19 on the construction sector through a meta-analytical examination. For this purpose, a wide literature review was conducted, and the studies obtained were filtered and analyzed. The literature findings revealed that during the pandemic period, the construction sector faced labor shortages, difficulties in project financing, and experienced delays and cost increases in projects due to supply chain disruptions. Furthermore, productivity decreased due to employee mental and psychological problems. Based on the findings derived from the investigation carried out via meta-analysis, it was determined that the prominent effects of COVID-19 on the construction sector include cost increases due to production factors, supply chain issues, suspension of projects, a decrease in demand for construction projects, and the emergence of quality-related problems. As a result of the study, theoretical and practical recommendations were presented regarding the risks faced by construction enterprises in the event of a possible epidemic in the future.

Keywords: *construction industry, COVID-19, pandemic, sectoral impact*.

Introduction

The COVID-19 outbreak started in China in 2019 and quickly spread around the world. Many countries have implemented measures to stop the outbreak from spreading, including curfews, quarantines of infected individuals and contact persons, mask-wearing requirements, social distancing laws, limiting the number of people in closed areas, restricting domestic and international travel, and implementing a remote work system. To reduce the effects of COVID-19 on the workforce and economy, several nations have developed support packages that aid individuals, companies, or organizations in need (Ahmed et al., 2022; Ilatova et al., 2022; Radzi et al., 2022). In addition, uncertainties during the pandemic caused an environment of fear and panic, psychological effects on individuals, and anxiety problems (Ağar et al., 2022).

In the construction sector, the fact that the activities carried out in the construction site environment are not suitable for remote working and that social distancing practices negatively affect labor productivity has caused delays in construction projects (Agyekum et al., 2022; Ahmed et al., 2022; Araya et al., 2021; Gamil & Alhagar, 2020; Gara et al., 2022; Gumusburun Ayalp & Çivici, 2022; Isa et al., 2021; Rajendran & Hasmori, 2022). COVID-19 has also created a number of difficulties, including the problem of maintaining hygiene in communal areas such as dining halls, dormitories, and toilets, and the fear of workers contracting the virus or infecting family members (Ağar et al., 2022; Alhammadi, 2022; Gumusburun Ayalp & Çivici, 2022). The economic volatility of the period, combined with a drop in demand in the sector, led to reduced productivity and fear among workers (Gumusburun Ayalp & Çivici, 2022; King et al., 2022; Nguyen et al., 2021; Radzi et al., 2022; Rani et al., 2022). Employee anxiety and demotivation caused a decrease in stakeholder productivity. In addition to the economic impacts of COVID-19, the individual impacts experienced by employees have also had negative effects on companies and the sector (Alsharef et al., 2021; Rokooei et al., 2022).

There are numerous studies in the literature examining the impact of the COVID-19 pandemic on the construction sector (Agyekum et al., 2022; Ahmed et al., 2022; Alsharef et al., 2021; Araya et al., 2021; Gamil & Alhagar, 2020; Gara et al., 2022; Gumusburun Ayalp & Çivici, 2022; Ilatova et al., 2022; Isa et al., 2021; Kaushal & Najafi, 2021; Khalafallah et al., 2021; King et al., 2022; Nguyen et al., 2021; Olanrewaju et al., 2022; Radzi et al., 2022; Rajendran & Hasmori, 2022; Rani et al., 2022; Rehman et al., 2022). In these studies, issues affecting the construction sector during the COVID-19 process were mostly discussed in relation to countries such as Chile, Malaysia, Ghana, and Nigeria (Agyekum et al., 2022; Araya et al., 2021; Gara et al., 2022; Gumusburun Ayalp & Çivici, 2022; Ilatova et al., 2022; Isa et al., 2021; Khalafallah et al., 2021; Nguyen et al., 2021; Radzi et al., 2022; Rani et al., 2022; Rokooei et al., 2022). It is highlighted in the studies of Dobrucali et al. (2022) and Gumusburun Ayalp and Çivici (2022) that the parameters identified based on country can be unique to the characteristics of the regions. Since most studies on the topic are local in nature, the findings' global validity is weak. Consequently, this study conducted a systematic literature review and used the meta-analysis method to thoroughly examine the effects of the COVID-19 process on the construction sector. It will be easy for companies to recognize dangers and take the necessary precautions in the case of a probable pandemic if they are aware of the sectoral effects of the outbreak beforehand. Furthermore, it is anticipated that this research will make significant contributions to future investigations into the ways in which the pandemic process has affected the construction industry.

Materials and Methods

This study reviewed studies on the factors affecting the construction sector during the COVID-19 outbreak and conducted a comprehensive literature analysis. As a result of searches in the Google Scholar, Science Direct, Emerald Insight, Springer, Taylor & Francis, ResearchGate, and Web of Science databases using the keywords "construction sector", "COVID-19", "pandemic" and "impact" 29 studies were found. Then twelve studies that ranked the factors affecting the construction sector using statistical techniques (such as the relative importance index (RII) and descriptive statistical analysis) were analyzed. This study presents the common factors found in at least three of these studies.

Common factors in the studies were identified using MS Excel spreadsheets. The studies that contain the detected factor are listed in the tables, together with the statistical rankings (RII and mean) and sample size of that factor in the pertinent research. Then, the steps given in Table 1 by (Neyeloff et al., 2012; Oo et al., 2023) were used to calculate the effect summary ($\overline{es}_v$) of the identified factors. The $\overline{es}_v$ in this study were calculated as weighted averages. Effect summary were calculated by performing these procedures for all identified factors.

Table 1. Meta-analysis steps (Oo et al., 2023).

Step		Abbrev.	Equation
1	Calculate the effect size of individual factor (i.e. the RII)	es	
2	Calculate the standard error	SE	$SE = \frac{es}{\sqrt{es * n}}$ n=sample size
3	Compute the within-study variance	Var	$Var=SE^2$
4	Calculate the individual study weight	w	$w=\frac{1}{SE2}$
5	Compute the total variance, Q (within-studies variance plus the between-studies variance). Q statistic is a measure of heterogeneity across selected studies. It is distributed as a chi-square statistic with k (number of studies) – 1 degrees of freedom	Q	$Q = \sum(w * es^2) - \frac{[\sum(w * es)]^2}{\sum w}$
6	Compute I^2, an alternative measure to quantify heterogeneity in percentage, providing a measure of the degree of inconsistency in the studies' results (Higgins, 2003). Negative values of I^2 are put equal to zero so that I^2 lies between 0 and 100%. A value of 0% indicates no observed heterogeneity, and larger values show increasing heterogeneity	I^2	$I^2 = \frac{Q - df}{Q} x100$
7	Compute the between-studies variance	v	$v = \frac{Q-df}{\sum w - \left(\frac{\sum w^2}{w}\right)}$ if $Q > df$ $v = 0$, if $Q \leq df$ df=degrees of freedom, k (number of studies) – 1
8	Calculate the new weight of individual study under the random-effects model specification	w_v	$w_v = \frac{1}{SE^2 + v}$
9	Calculate the effect summary (i.e. weighted RII) using the new weight from Step 8	$\overline{es}_v$	$\overline{es}_v = \frac{\sum(w_v * es)}{\sum w_v}$

Findings

In this study, through a literature review, the commonly observed impacts of COVID-19 on the construction sector between 2020 and 2023 were determined by examining studies aimed at identifying these effects (Gamil & Alhagar, 2020; Araya et al., 2021; Isa et al., 2021; Agyekum et al., 2022; Ahmed et al., 2022; Gumusburun Ayalp & Çivici, 2022; Khalafallah et al., 2021; King et al., 2022; Rajendran & Hasmori, 2022; Rani et al., 2022; Alhammadi, 2022; Jang et al., 2023). These identified effects were aggregated under seventeen main headings, and effect summary ($\overline{es}_v$) values were calculated (Table 2). Upon examination of the results, it is observed that cost increases due to production factors, supply chain issues, project suspensions, a decrease in demand for construction projects, and quality-related issues rise to prominence.

Table 2. Magnitude of the effects of the COVID-19 pandemic on the construction sector.

Factor Num.	The Effects of COVID-19 on the Construction Sector	$\overline{es}_v$	Number of References
F1	Cost Increase Due to Production Factors	**0,768**	**7**
F2	Supply Chain Issues	**0,737**	**8**
F3	Suspension of Projects	**0,692**	**7**
F4	Decrease in Demand for Construction Projects	**0,686**	**6**
F5	Quality-related Issues	**0,681**	**3**
F6	Communication Deficiencies Among Project Stakeholders	**0,632**	**4**
F7	Disruptions in Work Schedule	**0,600**	**4**
F8	Delays in Projects	**0,574**	**9**
F9	Concerns about carrying on with construction work.	**0,555**	**5**
F10	Requests for Changes in Contract Scope	**0,555**	**5**
F11	Employee Layoffs	**0,405**	**5**
F12	Difficulties in Adapting to Health and Safety Issues Due to COVID-19	**0,377**	**5**
F13	Financial Challenges	**0,261**	**11**
F14	Labor Shortages in the Sector	**0,229**	**11**
F15	Decreases in Productivity	**0,213**	**8**
F16	Difficulties in Material Procurement	**0,139**	**8**
F17	Mental and Emotional Health Issues	**0,137**	**7**

Based on the examined literature studies, it has been determined that the main reasons for cost increases in the construction sector due to production factors (F1) are factors reducing production capacity in factories during the pandemic (Amien et al., 2023; Bhatt et al., 2022; Central Statistics Office, 2022) and disruptions in the supply chain (F2) (Gara et al., 2022; Gumusburun Ayalp & Çivici, 2022;Olanrewaju et al., 2022; Rani et al., 2022; Rokooei et al., 2022) and difficulties in accessing the labor force (F14) (Gara et al., 2022; Gumusburun Ayalp & Çivici, 2022; King et al., 2022; Rajendran & Hasmori, 2022; Rani et al., 2022). Implementation of national and international travel bans caused disruptions in raw material supply and material production (F16); this also brought about problems in material supply (F2) and price increases. Restrictions or disruptions experienced during the pandemic process resulted in delays on a project basis (F7) or in milestone tasks (F8) (URL-1, 2024). The pandemic's unpredictability caused the clauses in contracts regarding force majeure to be insufficient and change claims (F10) became inevitable (Gamil & Alhagar, 2020; Khalafallah et al., 2021; Agyekum et al., 2022; Ahmed et al., 2022). The difficulty in inspection due to reduced teams, quarantine, and remote working has caused quality-related problems (F5) (Nguyen et al., 2021; Ahmed et al., 2022; Rajendran & Hasmori, 2022). Financial difficulties experienced by companies (F13) (Gamil & Alhagar, 2020; Khalafallah et al., 2021; Nguyen et al., 2021; Agyekum et al., 2022; Ahmed et al., 2022; Gara et al., 2022; Gumusburun Ayalp & Çivici, 2022; Rajendran & Hasmori, 2022) have directed them to practices such as contraction

(F11) and laying off employees or giving compulsory unpaid leave. Since companies have been concerned about carrying on with the sector (F9) due to duration and financial difficulties in supplying resources, they have preferred a strategy of suspending planned investments (F3) in order to cope with these difficulties (Agyekum et al., 2022; Ahmed et al., 2022; Gamil & Alhagar, 2020; Gumusburun Ayalp & Çivici, 2022; Isa et al., 2021). Uncertainty in the sectors negatively affected investors' risk appetite for new projects (F4) (Agyekum et al., 2022; Ahmed et al., 2022; Gamil & Alhagar, 2020; Gumusburun Ayalp & Çivici, 2022; Isa et al., 2021). In continuing projects, the measures taken in the construction site environment, quarantine practices in the workforce (F12), or the psychological effects of the risk of getting sick have made it difficult to focus on production, causing a decrease in productivity and an increase in quality-related problems (Nguyen et al., 2021; Ahmed et al., 2022; Rajendran & Hasmori, 2022). The rapid and mandatory transition to the remote working system has brought about coordination problems between stakeholders (F6) (Gumusburun Ayalp & Çivici, 2022). The environment of uncertainty during the pandemic period has led to financial and emotional concerns among employees, loss of motivation, and restrictions on workers' movements due to the measures taken, which have resulted in decreased productivity (F15) and workers experiencing mental and emotional issues (F17) (Agyekum et al., 2022; Ağar et al., 2022; Ahmed et al., 2022; Alsharef et al., 2021; Araya et al., 2021; Gumusburun Ayalp & Çivici, 2022; Ilatova et al., 2022; King et al., 2022; Nguyen et al., 2021; Radzi et al., 2022; Rajendran & Hasmori, 2022; Rani et al., 2022). Consequently, multiple effects of the COVID-19 pandemic on the construction industry, businesses, and employees have been identified; generating a direct or indirect chain reaction.

Conclusion and Recommendations

The negative effects of the pandemic on the economy have affected many sectors to a certain extent. When global sector reports and literature studies are examined, it is stated that the sector, companies and employees are affected by this process at different levels. This study is aimed at collectively evaluating the effects of COVID-19 on the construction industry identified in the literature. As a result of the systematic literature review conducted for this purpose, studies examining the effects of the epidemic on the construction industry during the COVID-19 epidemic were identified. Among the studies examined, those listing the factors affecting the construction industry during the COVID-19 epidemic were selected. After that, these factors were compiled under 17 main headings and ranked based on the effect summary ($\overline{\boldsymbol{es}}_v$) values obtained through meta-analysis. When the results are examined, it is seen that the top five effects of the COVID-19 pandemic on the construction sector, respectively, are: cost increases due to production factors, supply chain issues, project suspensions, decreased demand for construction projects, and quality-related problems.

Considering the interaction between the factors included in the study and the domino effect they create, it is believed that conducting production in a factory, where possible, in prefabrication may reduce quality-related issues or factors that decrease labor productivity on the construction site due to social distancing. Nevertheless, in such a scenario, governments must distribute their workforce to alternative industries and promote new enterprises in order to mitigate the negative impact of a transition to automated manufacturing on employment.

It is recommended to improve communication between stakeholders for the coordination problem between teams, especially due to remote working during the pandemic period, and it is thought that prioritizing the use of the Building Information Modeling system by companies will facilitate the adaptation of the company in the event of a new epidemic. Additionally, in building production models where production is carried out on the construction site; the utilization of unmanned aerial vehicle (UAV/drone) technologies will be helpful in remote construction site inspections to a certain extent.

The people-oriented structure of the sector reveals that the epidemic is a significant source of risk to labor resources. While the decrease in workforce productivity during the pandemic is primarily attributed to social distancing rules, it should be noted that psychological factors also play a role, and companies are advised to use a suitable communication method that supports the "mental well-being of employees" and alleviates anxiety-inducing situations such as "fear of job loss".

It is important for companies to monitor international pandemics and revise their supply and work schedules in advance to reduce the impacts of the process. Including pandemics as force majeure in contracts and supporting them with more detailed regulatory clauses will contribute to reducing disputes between parties. Additionally, it is important for companies to develop emergency plans, hygiene, and safety procedures that consider potential risks, likely enabling them to respond quickly to pandemic situations.

As a result of the COVID-19 pandemic beginning in 2019, this research examines a restricted number of studies. Even though the COVID-19 pandemic period has ended, it has been observed that post-COVID effects are still being studied in the healthcare field. It is recommended that in future studies, the post-COVID effects be examined specifically for construction sector workers as well.

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References

Agyekum, K., Kukah, A. S., & Amudjie, J. (2022). The impact of COVID-19 on the construction industry in Ghana: The case of some selected firms. *Journal of Engineering, Design and Technology*, *20*(1), 222-244. https://doi.org/10.1108/JEDT-11-2020-0476

Ağar, A., Tuğrul, I., & Atalı, G. (2022). Yüksek hızlı tren tünel inşaatı projesi çalışanlarının Covid-19 salgınına yönelik algı ve tutumlarının incelenmesi. *Gumushane University Journal of Health Sciences*, *11*(2), 738-747.

Ahmed, S., Haq, I., & Anam, S. M. A. (2022). Impacts of COVID-19 on the construction sector in the least developed countries. *International Journal of Building Pathology and Adaptation*, *December 2019*. https://doi.org/10.1108/IJBPA-04-2022-0059

Alhammadi, S. A. (2022). Factors affecting the management of Riyadh's construction sector in the light of COVID-19. *Heliyon*, *8*(11), e11899. https://doi.org/10.1016/j.heliyon.2022.e11899

Alsharef, A., Banerjee, S., Uddin, S. M. J., Albert, A., & Jaselskis, E. (2021). Early impacts of the COVID-19 pandemic on the United States construction industry. *International Journal of Environmental Research and Public Health*, *18*(4), 1559. https://doi.org/10.3390/ijerph18041559

Araya, F., Sierra, L., & Basualto, D. (2021). Identifying the impacts of COVID-19 on Chilean construction projects. *Lecture Notes in Civil Engineering*, *251*(December), 623-635. https://doi.org/10.1007/978-981-19-1029-6_47

Dobrucali, E., Sadikoglu, E., Demirkesen, S., Zhang, C., & Tezel, A. (2022). Exploring the impact of COVID-19 on the United States construction industry: Challenges and opportunities. *IEEE Transactions on Engineering Management*, *April 2020*, 1-13. https://doi.org/10.1109/TEM.2022.3155055

Gamil, Dr. Y., & Alhagar, A. (2020). The impact of pandemic crisis on the survival of construction industry: A case of COVID-19. *Mediterranean Journal of Social Sciences*, *11*(4), 122-128.

Gara, J. A., Zakaria, R., Aminudin, E., Yahya, K., Sam, A. R. M., Loganathan, Munikanan, V., Yahya, M. A., Wahi, N., & Shamsuddin, S. M. (2022). Effects of the COVID-19 pandemic on construction work progress: An on-site analysis from the Sarawak construction project, Malaysia. *Sustainability (Switzerland)*, *14*(10). https://doi.org/10.3390/su14106007

Gumusburun Ayalp, G., & Çivici, T. (2022). Factors affecting the performance of construction industry during the COVID-19 pandemic: A case study in Turkey. *Engineering, Construction and Architectural Management*. https://doi.org/10.1108/ECAM-10-2021-0890

Higgins, J. P., Thompson, S. G., Deeks, J. J., & Altman, D. G. (2003). Measuring inconsistency in meta-analyses, *BMJ*, *327*(7414), 557-560. https://doi.org/10.1136/bmj.327.7414.557

Ilatova, E., Abraham, Y. S., & Celik, B. G. (2022). Exploring the early impacts of the COVID-19 pandemic on the construction industry in New York State. *Architecture*, *2*(3), 457-475. https://doi.org/10.3390/architecture2030026

Isa, C. M. M., Nusa, F. N. M., Ishak, S. Z., & Fam, S. F. (2021). Impacts of COVID-19 pandemic on the road and transport sectors using relative importance index. *2021 IEEE International Conference on Automatic Control and Intelligent Systems, I2CACIS 2021 - Proceedings*, *June*, 305-310. https://doi.org/10.1109/I2CACIS52118.2021.9495908

Kaushal, V., & Najafi, M. (2021). Strategies to mitigate COVID-19 pandemic impacts on health and safety of workers in construction projects. *Civil Engineering Beyond Limits*, *2*(2), 1-8. https://doi.org/10.36937/cebel.2021.002.001

Khalafallah, A., Soliman, E., & Alrasheed, K. (2021). Impacts of COVID-19 on the Middle East construction industry. *Journal of Engineering Research (Kuwait)*, *10*(3), 34-58. https://doi.org/10.36909/jer.14823

King, S. S., Rahman, R. A., Fauzi, M. A., & Haron, A. T. (2022). Critical analysis of pandemic impact on AEC organizations: The COVID-19 case. *Journal of Engineering, Design and Technology*, *20*(1), 358-383. https://doi.org/10.1108/JEDT-04-2021-0225

Neyeloff, J. L., Fuchs, S. C., & Moreira, L. B. (2012). Meta-analyses and Forest plots using a microsoft excel spreadsheet: Step-by-step guide focusing on descriptive data analysis. *BMC Research Notes*, *5*(1), 52. https://doi.org/10.1186/1756-0500-5-52

Nguyen, V. T., Nguyen, B. N., Nguyen, T. Q., Dinh, H. T., & Chu, A. T. (2021). The Impact of the COVID-19 on the construction industry in Vietnam. *International Journal of Built Environment and Sustainability*, *8*(3), 47-61. https://doi.org/10.11113/ijbes.v8.n3.745

Jang, J.-H., Hong, R.-L., Lee, K.-T., & Kim, J.-H. (2023). A comprehensive approach to capturing the impact and identifying countermeasures of the COVID-19 pandemic at construction sites in the Republic of Korea. *Buildings*, *14*(1), 30. https://doi.org/10.3390/buildings14010030

Olanrewaju, O. I., Chileshe, N., Adekunle, E. O., & Salihu, C. (2022). Modelling the environmental, economic, and social impacts of coronavirus pandemic on the construction industry. *International Journal of Construction Management*, 1-14. https://doi.org/10.1080/15623599.2022.2120077

Oo, B. L., Lim, B. T. H., & Runeson, G. (2023). Mark-up on construction projects: What have we learnt in the last 20 years? *Engineering, Construction and Architectural Management*, *30*(9), 4319-4338. https://doi.org/10.1108/ECAM-01-2022-0070

Radzi, A. R., Rahman, R. A., & Almutairi, S. (2022). Modeling COVID-19 impacts and response strategies in the construction industry: PLS–SEM approach. *International Journal of Environmental Research and Public Health*, *19*(9). https://doi.org/10.3390/ijerph19095326

Rajendran, Y., & Hasmori, M. F. B. (2022). The impact of Covid-19 pandemic to the construction industry in Malaysia. *Recent Trends in Civil Engineering and Built Environment*, *3*(2), 1586-1595. https://doi.org/https://doi.org/10.30880/rtcebe.2022.03.01.177

Rani, H. A., Farouk, A. M., Anandh, K. S., Almutairi, S., & Rahman, R. A. (2022). Impact of COVID-19 on construction projects: The case of India. *Buildings*, *12*(6), 1-20. https://doi.org/10.3390/buildings12060762

Rokooei, S., Alvanchi, A., & Rahimi, M. (2022). Perception of COVID-19 impacts on the construction industry over time. *Cogent Engineering*, *9*(1). https://doi.org/10.1080/23311916.2022.2044575

Sami Ur Rehman, M., Shafiq, M. T., & Afzal, M. (2022). Impact of COVID-19 on project performance in the UAE construction industry. *Journal of Engineering, Design and Technology*, *20*(1), 245-266. https://doi.org/10.1108/JEDT-12-2020-0481

The Effects of Building Interventions in Utilization Phase on Earthquake Resistance

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Abstract

Earthquakes are an inevitable reality in Turkey and the country has suffered from many devastating earthquakes throughout history. Many buildings have been severely damaged and have become unusable after earthquakes. One of the reasons for damage to the buildings is that the users make interventions in the buildings during the utilization phase in line with their requirements. These changes reduce the earthquake resistance of the structures.

The buildings have many interventions in utilization phase. Considering the damage caused by earthquakes in our country, the evaluation of building interventions has a great importance. In this study, the most encountered interventions in the utilization of buildings will be determined from the literature and their existing examples will be revealed. While the effects of the interventions on the existing buildings on the earthquake resistance are evaluated within the scope of the study, the provisions of the legislation regarding the interventions are also examined. As a result, it has been determined that unconscious interventions affect the stability of the structures negatively and may cause them to be damaged or even collapsed in an earthquake.

Keywords: *building interventions, earthquake, earthquake damages, earthquake resistance*

Introduction

In Turkey's historical process, many destructive earthquakes have occurred, many buildings have collapsed and been damaged, and many people have lost their lives. The earthquakes on February 6, 2023, caused many buildings to collapse and suffer severe damage in cities such as Kahramanmaraş, Gaziantep, Şanlıurfa, Diyarbakır, Adana, Adıyaman, Osmaniye, Hatay, Kilis, and Malatya, resulting in the loss of many lives. As of February 13, 2023, according to official figures, 6,444 buildings collapsed, and reports of 11,302 buildings being at risk of collapse were received (IMO, 2023). According to AFAD's announcement on March 20, 2023, 50,096 people lost their lives in the region (MO, 2023).

Most of the studies and reports in the existing literature focus on evaluating design errors, material quality, structural irregularities, and existing regulations regarding earthquake damage. Considering the damage to buildings, it has been observed that decisions made at every stage of the building production process and practices implemented are effective in building damages.

Inefficient urban planning in weak ground conditions, cities planned on productive lands, and urban planning allowing high-rise buildings affect decisions made during the planning phase. Damage and collapses caused by material weaknesses and constructive weaknesses result from what is done in practice and the failure of the inspection system. Damage caused by structural irregularities affects decisions made during the design phase. However, changes made during the usage phase of buildings can also lead to structural irregularities. In the existing literature and reports, errors related to the usage phase were only encountered in the Chamber of Architects' report dated May 2, 2023. In the relevant report, damage caused by interventions during the usage phase and the passing of installations through load-bearing structural elements were among the reasons for damage (MO, 2023). Other than that, no studies were found in the Turkish literature regarding the effect of building interventions during the usage phase on earthquake resistance. Buildings undergo many changes during the usage phase, often without official permits and inspections, and these changes can adversely affect the earthquake resistance of the building. Within the scope of this study, building interventions during the usage phase will be identified from the literature, examples will be presented, and the effects of interventions on earthquake resistance will be evaluated within the framework of existing legislation. In the study to be conducted, building interventions during the usage phase in reinforced concrete skeleton buildings, which constitute 97% of the buildings receiving building permits according to the data of the Turkish Statistical Institute (TUIK, 2020), will be examined for their effects on earthquake resistance.

Method of Study

In this study, we aim to analyze the impact of interventions on buildings during their usage phase on their earthquake resistance. The steps of methodology are seen in Figure 1.

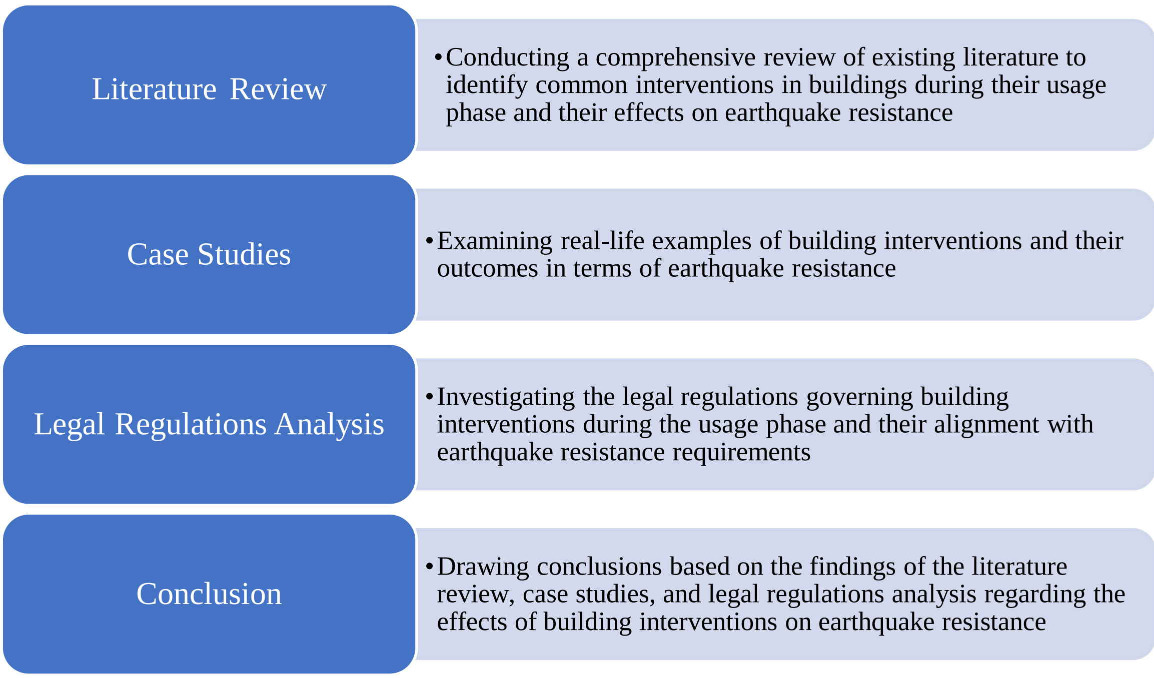

Figure 1: Steps of methodology.

This study aims to determine whether the building interventions during the use phase are present on the earthquake cracks, to further evaluate the interventions and not to contribute to them.

Assessment of Building Interventions in Utilization Phase (Literature Review, Case Studies and Legal Regulations Analysis)

With the advancement of technology, user needs change over time. Over time, even in existing cities, the functions of buildings can change, residential areas can transform into commercial areas. For example, it is observed that a building designed as a residence can be converted into a store, shop, or office (Moosavi, 2013). The user of the building product produced in the construction sector is not always known before production. Especially in housing production, buildings are produced in a standardized manner that does not meet the needs of every user, and users may have to live under conditions they are not satisfied with. these changes made in buildings lead to irregularities in the buildings and thus negatively affect the building and the people living inside in possible earthquakes (Hürol, 2014). The damages and collapsed buildings in the earthquakes of February 6, 2023, also prove this situation.

The earthquake damages caused by interventions in the use process of buildings were classified into six groups, and the interventions and their behavior against earthquakes were evaluated.

Changes in Building Functions

In the conclusion of the IMO Earthquake Preliminary Assessment Report, the absence of infill walls in commercial spaces on the ground floors is considered one of the main reasons for the damage. It is frequently encountered in collapsed buildings in earthquakes where the ground floors collapse first, followed by the sandwich stacking of the upper floors (IMO, 2023). With the increase in commercial functions in cities, some buildings originally designed for residential, or basement purposes are converted into shops and stores, leading to the removal of infill walls on the ground floor. This situation leads to the formation of weak floors. Weak floors emerge as one of the most significant causes of damage in collapsed buildings. In Figure 2, examples of weak floors are observed where walls are removed or the amount of walls is significantly reduced due to changes in ground floor usage.

Figure 2: Examples of the removal of infill walls due to the conversion of basement floors into shops (from Esra Bostancıoğlu archive, Adapazarı).

In some buildings, apartments are converted into commercial spaces, so interior walls are removed, relocated, and exterior walls are either removed or reduced to make the facade more transparent. Figure 3 illustrates an example where the apartments on the lower floors of a residential building are converted into commercial spaces, the walls on the facade are removed to make it completely transparent, and balconies are integrated into the interior spaces.

Figure 3: An example of residential buildings being converted into commercial spaces, turning into stores (with a significant portion of exterior and interior walls removed) (From Esra Bostancıoğlu archive, Adapazarı).

Changes in Interior Spaces According to User Expectations

Buildings undergo changes over time according to the needs, tastes, and expectations of users. One of the most common types of interventions in buildings is the addition or removal of infill walls (Güler, 2021). User needs can be categorized into psychological, physical, and material needs (Özen, 2018). As families grow, there arises a need for specialized spaces for new family members. Therefore, room numbers are increased by adding new walls to create larger spaces. Sometimes, infill walls are removed to obtain larger and more spacious areas.

According to the Planned Areas Zoning Regulation, interior interventions that do not affect the load-bearing system are not subject to inspection. There are studies in the literature on the effect of infill walls on earthquake resistance. Baran examined framed structures with and without infill walls under lateral and low load effects (Baran, 2012). In his results, he demonstrated that infill walls increase the load-bearing capacity of the frame by 3.5 times. In another study, Demirel and colleagues compared the base shear forces of structures without walls, with infill walls, and with double wire mesh reinforced walls. The shear force of infill walls is 43% higher than that of an empty frame (Demirel et al., 2015). In the load-bearing system, the presence of infill walls between the skeleton increases the stability of the load-bearing system.

Interventions on Structural System Elements

Interventions on structures must be carried out within the scope permitted by regulations to ensure the safety of life and property. Otherwise, adverse consequences such as building collapse and loss of life may occur. The reason for the collapse of Nezir Baş Apartment in Van during the Van Earthquake in 2011 was found to be the removal of columns due to the conversion of the ground floor into a car gallery (NTV, 2011).

Openings made in vertical load-bearing shear walls affect the stability of the structure and reduce earthquake resistance. In the earthquake that occurred on February 6, 2023, it was observed that some buildings had later interventions in reinforced concrete shear walls where parts were drilled or cut. Especially, passing plumbing elements through load-bearing system elements such as shear walls and beams is a commonly encountered situation. As seen in Figure 4, cutting or drilling of reinforced concrete shear walls in the basement of Adıyaman Özel Gözde Medical Center to pass plumbing and ventilation pipes is an example of this (ITU, 2023).

Alteration of Window Sizes and Shapes

In the preliminary assessment report of the earthquake on February 6, 2023, by IMO, short columns are defined as "band windows that are opened from end to end between columns on one axis and have a low height according to the floor height, causing the column to lose strength and become ineffective primarily due to short column behavior resulting from shear failure of the column." The report states that short column damage was observed in heavily damaged structures (IMO, 2023).

Changes in window sizes and shapes during the use of buildings can lead to interventions that may cause the formation of short columns. As seen in Figure 5, band windows on the basement floor can cause the formation of short columns, leading to damage.

Figure 4: Cut reinforced concrete shear wall at Adıyaman Özel Gözde Medical Center (Example of structural element intervention) (ITU, 2023).

Figure 5: Damage to band windows in a building during the 2020 Izmir Earthquake (IMO, 2020).

Formation of Gaps in Slabs

Gaps opened in slabs can lead to irregularities in the plan. According to the Turkish Earthquake Building Code, the total area of gaps in a floor should not exceed one-third of the gross floor area (Turkish Earthquake Building Code, 2018). Users or property owners often combine apartments on two different floors to create duplex units (Figure 7). Reinforcement is present in reinforced concrete slabs, and if a significant portion of the reinforcement in one direction is cut due to an intervention to remove part of the slab, the seismic resistance of the slab will decrease (Hürol, 2013). Additionally, to mitigate the negative impact of slab gaps, the dimensions of the elements and the amount of reinforcement need to be increased for slab strengthening purposes (Coza, 2003). Particularly in stores, one common intervention during use is the widening of existing stairs due to insufficient width. Consequently, if a slab is to be removed, structural engineers must evaluate the building according to new findings and thoroughly examine the structure to prevent different types of irregularities such as ground irregularities, etc. (Moosavi, 2013).

Addition of Rooftop Floors

The inclusion of rooftop floors in buildings is also an intervention carried out by users (Figure 7). Adding unauthorized floors to buildings, constructing additional floors, and thus exceeding the loads calculated in the project all signify the same thing (İlki et al., 2008). Evaluations conducted following the earthquakes on February 6, 2023, revealed that unauthorized constructions caused damage and collapse in buildings (MO, 2023).

Conversion of Open Projections into Enclosed Extensions to Incorporate Spaces

The desire of users to have larger living spaces due to dissatisfaction has been highlighted in various studies (Korkmaz, 2001). Open projections are enclosed and incorporated into spaces to enlarge indoor areas. Especially in countries like India, Algeria, Northern Cyprus, and Turkey, closing balconies to expand room sizes is seen as possible changes in use (Murty et al., 2006).

Figure 7: Three independent additional spaces are observed on the roof of the building, with the addition of three separate stairs and the creation of gaps in the slabs (From Bostancıoğlu archive, Istanbul).

Figure 8: An example where open projections are transformed into enclosed extensions and incorporated into interior spaces (From Esra Bostancıoğlu archive, Adapazarı)

Article 59 of the Planned Areas Zoning Regulation dated July 3, 2017, describes the application of folding, opening, and closing glass panels on balconies as "simple renovation" and does not require any formal permission. However, in these renovations, it is quite common to see practices where balconies lose their function, the wall between the balcony and the room is removed, and the balcony is included in the room to enlarge the rooms. With the removal of the wall, the stability of the load-bearing system of the reinforced concrete skeleton system varies, and damage can be inflicted on the load-bearing system elements during the process of removing the wall. An example of balconies being closed to increase the areas of spaces within the building is seen in the Figure 8.

Conclusion and Recommendations

The "Planned Areas Zoning Regulation" published in the Official Gazette dated 03.07.2017, which covers interventions in existing buildings in Turkey, categorizes interventions into two groups: "simple renovation" and "substantial renovation." No permission is required for applications carried out under "simple renovation." Practices such as folding, opening, and closing balconies with glass panels, partition walls, garden walls, wall coverings, chimneys, eaves, roofs, and similar elements, as well as changes in the interior design of spaces and changes in the list of spaces that do not affect the load-bearing system and fire safety are considered as simple renovations. However, it has been demonstrated in the literature that infill walls also have a positive effect on seismic resistance. Therefore, it is considered that the evaluation of interventions made in partition walls and changes in interior design as simple renovations may not be entirely correct. Changes made in the interior space, such as adding or removing walls, are common renovations encountered in existing buildings.

The conversion of open projections into enclosed extensions, i.e., closing balconies, is also considered within the scope of simple renovation. However, these practices often accompany changes in interior walls. Those who close the balcony often remove the wall between the balcony and the room to further expand the space. Passing plumbing pipes through load-bearing system elements is also a very common intervention and affects the load-bearing system stability of buildings. Due to functional changes, the removal or significant reduction of infill walls in buildings where ground floors are converted to commercial functions leads to the formation of weak floors. It has been determined through Earthquake Reports that weak floors and soft stories are among the most important causes of damage.

In conclusion, it has been observed that interventions (renovations) carried out in buildings during use have an impact on the seismic resistance of structures. Recording and inspecting all interventions, regulating regulations to control all renovations, raising awareness among users and implementers about the renovations, and popularizing earthquake awareness throughout society will contribute to interventions being carried out consciously and buildings suffering less damage or no damage during earthquakes.

References

Baran, M. (2012). Dolgu Duvarların Betonarme Çerçeveli Yapıların Davranışı Üzerindeki Etkilerinin İncelenmesi. *Gazi Üniversitesi Mühendislik Mimarlık Fakültesi Dergisi*, 27(2), 275-284.

Coza, H. (2003). *Betonarme yapılarda gözlenen deprem hasarları ve nedenleri (The earthquake damages in reinforced concrete structures)* [Unpublished master thesis]. Istanbul Technical University.

Demirel, İ. Ö., Yakut, A., Binici, B., & Canbay, E. (2015). Betonarme çerçevelerde dolgu duvar etkisinin incelenmesi üzerine deneysel çalışma (Experimental study on the investigation of infill wall effect in reinforced concrete frames). *3. Türkiye Deprem Mühendisliği ve Sismoloji Konferansı (3rd Turkish Earthquake Engineering and Seismology Conference),* 14-16 October, İzmir, Turkiye.

Guler, K. (2021). Yığma binaların deprem güvenliği ve performansı (Earthquake safety and performance of masonry buildings). *ITU Vakfı Dergisi,* 86, 6-10.

Hurol, Y. (2014). On ethics and the earthquake resistant interior design of buildings. *Science and Engineering Ethics*, 20, 171-181.

Ilki, A., & Celep, Z. (2012). Earthquakes, existing buildings and seismic design codes in Turkey. *Arabian Journal for Science and Engineering*, 37, 365-380.

Istanbul Technical University (ITU). *6 February 2023 04.17 Mw 7.8 Kahramanmaraş, Hatay and 13.24 Mw 7.7 Kahramanmaraş Earthquakes Preliminary Investigation Report*. (https://haberler.itu.edu.tr/haberdetay/2023/03/24/itu-den-2023-nihai-deprem-raporu).

Korkmaz, S. Z. (2001). *Tek aile evlerinde tasarıma katılımın kullanıcı memnuniyetine etkisinin incelenmesi (In single family houses effects of participation on user statisfaction)* [Unpublished master thesis]. Selcuk University.

Moosavi, M. S. F. (2013). *Effect of interior changes on earthquake resistance of buildings-case: reinforced concrete frame system* [Unpublished master thesis]. Eastern Mediterranean University.

Murty, C.V.R., Charleson, A.W., & Sanyal, S.A. (2006). *Earthquake Design Concepts for Teachres of Architecture Colleges*. National Information Center of Earthquake Engineering, India: IIT Kanpur.

NTV News, 2011, https://www.ntv.com.tr/turkiye/kolonlar-oto-galeri-icin-kesilmis,Q904LupegUCxjDoeMgj92Q)

Özen, R. S. (2018). *Mimari tasarımda betonarme yapıların Türk Deprem Yönetmeliği açısından taşıyıcı sistem düzensizliğinin değerlendirilmesi (Evaluation of structural system irregularities of reinforced concrete buildings according to Turkish Earthquake Code in architectural design stage)* [Unpublished master thesis]. Selcuk University.

Planned Areas Zoning Regulation (2017). Official Gazette dated 03/07/2017 and numbered 30113. Ministry of Environment, Urbanization and Climate Change.

TMMOB Chamber of Civil Engineers (IMO). *Report on the Izmir Earthquake that occurred on October 30, 2020*. IMO Izmir Branch.

TMMOB Chamber of Civil Engineers (IMO). (2023). *6 February 2023 Kahramanmaraş Pazarcık and Elbistan Earthquakes Preliminary Evaluation Report.* (https://www.imo.org.tr/Eklenti/8175,imo-deprem-raporu-2pdf.pdf?0)

TMMOB Chamber of Architects (MO). (2023). *6 February 2023 Earthquakes Detection and Evaluation Report.* http://www.mo.org.tr/_docs/MODEPREMRAPOR2.pdf

TUIK, Turkish Statistical Institute, https://www.tuik.gov.tr

Türkiye Earthquake Regulation, 2018. Official Gazette, 18 March 2018.

Identification and Assessment of Risk Factors Affecting Post-Disaster Reconstruction Projects

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Abstract

The increasing pace of climate change and urbanization has recently maximized the severity and frequency of disasters. Natural disasters pose a serious threat to society by deteriorating the societies' physical, environmental, economic, and social wellness. Post-disaster reconstruction projects are often deemed as key to relieving these stresses on the societies since these projects are commenced rapidly after a disaster to replace damaged social and critical infrastructures. Considering that post-disaster reconstruction projects are fast-tracked projects that are undertaken in a dynamic and turbulent post-disaster environment, they become vulnerable to a variety of risks stemming from the uncertainties. These risks should be identified and assessed properly to avoid cost overruns and substantial delays in these projects. Otherwise, full recovery of a community from a disaster can hardly be achieved. Examining the existing literature, risks that exist in the post-disaster reconstruction projects have not been identified and assessed, which, in turn, decision-makers are provided with limited knowledge about the potential risks of these projects. Thus, this study aims to identify and assess the risks that exist in post-disaster reconstruction projects. An in-depth literature review was initially conducted to get deep insight into studies focusing on post-disaster reconstruction projects. Next, the knowledge acquired during this literature review was used to synthesize risk factors that may escalate in these projects. Following this, a questionnaire survey was conducted with the participation of construction practitioners to assess the relative importance of the risks that were identified through the literature review. Lastly, the fuzzy TOPSIS method was implemented to analyze the collected data.

Keywords: *Fuzzy TOPSIS, post-disaster reconstruction projects, risk assessment, risk identification.*

Introduction and Research Background

Disasters are deemed mostly as catastrophic events that inflict significant damage on the people, economies, and overall activities in the affected society. Depending on the nature of the disasters, the affected community or society might not recover on its own, needing aid at the national and/or international level. In theory, disasters are categorized as natural disasters and human-made disasters. Natural disasters are those caused by natural hazards while human-made disasters are triggered by human-made hazards. However, in practice, it is a challenging task to decide whether a particular disaster is natural or human-made. The reason is that almost all disasters can be considered human-made due to human failure to implement robust pre and/or post-disaster management plans (Remes et al., 2016).

The increasing pace of climate change and urbanization has maximized the severity and frequency of disasters. Around the globe, approximately 200 million people are affected by disasters annually and 65000 people lose their lives while many more become disabled (Saner et al., 2022). Disasters also pose a significant threat to Turkey, especially earthquakes. On February 6, 2023, earthquakes with the magnitude of 7.7 and 7.6 hit the southern part of Turkey, killing an average of 50000 people and directly affecting 9 million people. (Agency, 2023). Beyond the direct effects, the disasters have also significant secondary effects such as mass migrations, halts in the economic and social activities in the affected region (Ghannad et al., 2020; RICS, 2006). Thus, utmost attention should paid to disaster management to minimize the impact of the disasters.

Disaster management generally consists of two phases. These are the pre-disaster and the post-disaster phases, respectively. Pre-disaster phase involves the actions undertaken to intervene before an event occurs while the latter is the process consisting of emergency response, short-term recovery, and long-term recovery (Bahmani & Zhang, 2022). The principle of Built Back Better has recently been proposed as a viable solution to cope with the increasing pace and severity of disasters. The principle was first coined in a report issued by Clinton after the 2004 Indian Ocean tsunami (Khasalamwa, 2009). In the report, the Build Back Better principle was presented as an approach that is based on conducting recovery, reconstruction, and rehabilitation activities in the post-disaster period to increase the resilience of physical infrastructure and social systems. (UN Secretary-General, 2016). By doing so, the principle also enables decision-makers to enhance the resilience of the affected region to a level higher than in the pre-disaster period (Rad et al., 2022). Therefore, the concept becomes even more indispensable for maximizing the success of reconstruction projects (Charles et al., 2022). In case terms such as resilience and/or the Build Back Better principle are not implemented in post-disaster reconstruction projects, similar vulnerabilities are likely to be encountered in future disasters (Mannakkara et al., 2018). Last but not least, studies such as Chang et al. (2010), Charles et al. (2022), Hofmann (2022), and Yang and Cheng (2020) pinpointed the benefits of implementing the Built Back Better principle as an action to establishing and sustaining post-disaster resilience. Activities in the post-disaster phase have urgency and importance (Tavakoli Taba et al., 2020). Specifically from the perspective of post-disaster reconstruction projects, the complex and turbulent post-disaster environment brings additional uncertainties that might escalate the risks. In this context, post-disaster projects should be carried out with tailor-made managerial solutions. Especially, the risks that stem from the inherent complexities of the post-disaster environment and reconstruction projects, should be identified and properly responded to maximize the success of post-disaster management plans. Otherwise, significant deviations from the post-disaster management plans might be inevitable. Looking into existing literature, although many aspects of the post-disaster reconstruction projects are investigated by the researchers, a review of the existing literature presented in Section 2 reveals that the risks affecting post-disaster reconstruction projects have not been identified and assessed. This study therefore aims to identify and assess the risks affecting post-disaster reconstruction projects to shed light to provide decision-makers with fruitful information about risks. Accordingly, in the first stage, risks were identified through a comprehensive literature review. This was then followed by the the questionnaire survey stage that was conducted with the participation of experts having diverse experience about post-disaster reconstruction projects. Lastly, the dataset was evaluated by implementing Fuzzy Topsis analysis.

Research Gap Analysis

Post-disaster reconstruction projects vary significantly from conventional construction projects in terms of in terms of uncertainties and complexities (Siriwardhana & Kulatunga, 2023). Therefore, many studies were devoted to shed light on these differences. To examine these studies, an in-depth literature review was conducted within the scope of this research. Accordingly, the notable studies were deeply examined systematically to reveal their pros and cons in a similar manner conducted by Alizadeh et al. (2020). The results of this literature review are presented in Table 1.

Table 1. Result of the systematic literature review.

REF.	BRIEF SUMMARY
A	The research aimed to resolve the resource allocation problem that exists in post-disaster reconstruction projects. The results suggested that the efforts should devoted to legislation and policy, the construction sector, the construction market, and the transportation system.
B	Apart from other studies, this study integrated the Build Back Better principle into the design process of the reconstruction projects.
C	The study proposed a decision-making framework that guides the implementation of the “Build Back Better” principle in reconstruction projects.
D	The study revealed and prioritized the client expectations for the post-disaster reconstruction projects. The results highlighted that on-time delivery, availability of resources, and communication techniques are the top three expectations of the clients.
E	The research integrated the sustainability indicators into post-disaster reconstruction projects. The results emphasized that sustainability is a significant concept that can maximize the success of reconstruction projects.
F	The study aims to explore organizational resilience practices in the construction industry. The results revealed inadequate organizational resilience practices within the industry.
G	The study clarified the objectives of post-disaster reconstruction projects. It was pinpointed that professional knowledge and the community’s knowledge should be jointly considered during the development and implementation of the reconstruction projects.
H	The study investigated the aspects of people-Centered Housing Recovery and the Build Back Better principle.
I	The study revealed the resilience factors that might maximize the resilience of post-disaster reconstruction projects. Furthermore, the study also proposed a framework for strategic decisions.
J	Given that reconstruction projects necessitate a significant amount of direct and indirect resources, it is almost impossible to undertake them simultaneously. Thus, this research developed a framework to prioritize these projects by considering the factors such as quality, robustness, and customer satisfaction.
K	The study identified and ranked the end-user-related resilience factors for the post-disaster reconstruction projects. By doing so, the decision-makers are provided with extensive knowledge about the resilience factors of the end-user perspectives.

Note: A: (Chang et al., 2010), B: (Mannakkara & Wilkinson, 2013), C: (Mannakkara & Wilkinson, 2014), D: (Aliakbarlou et al., 2017), E: (Ismail et al., 2017), F: (Sapeciay et al., 2017), G: (Fayazi & Lizarralde, 2018), H: (Maly, 2018), I: (Charles et al., 2022), J: (Mohammadnazari et al., 2022), K: (Charles et al., 2023).

Consequently, Table 1 reveals that there is an evident need to identify the risks of post-disaster reconstruction projects to minimize vulnerabilities of these projects.

Research Methodology

This study adopted the methodology shown in Figure 1. Accordingly, the methodology consists of two main parts: risk identification and risk assessment. In the risk identification part, a comprehensive review of the post-disaster reconstruction literature was conducted, and risks were identified. In the risk assessment part, a questionnaire survey and a fuzzy TOPSIS were jointly conducted to rank the identified risks with respect to time, cost, and quality criteria.

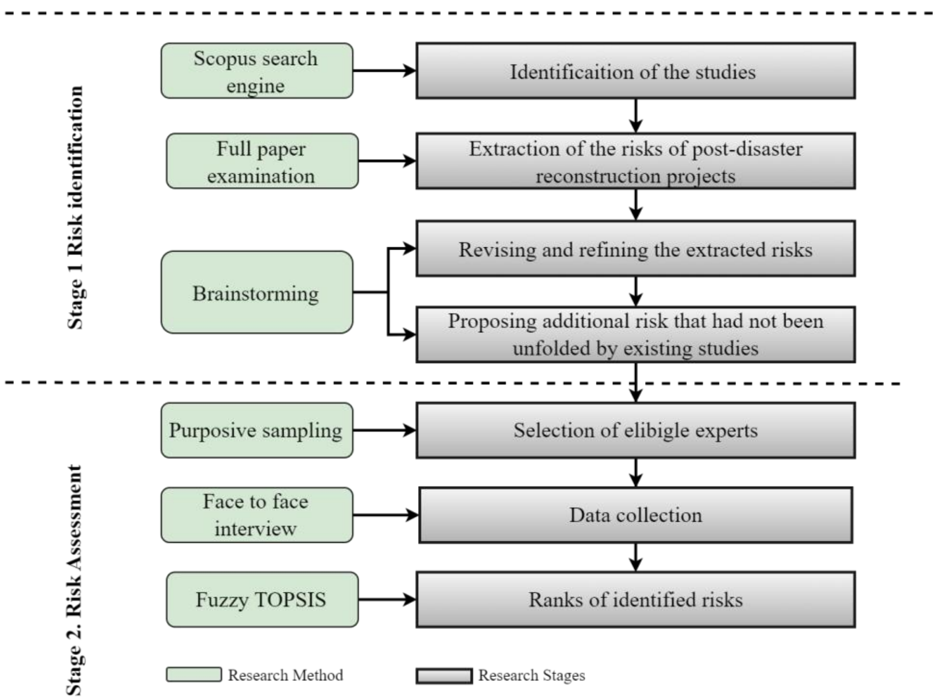

Figure 1: Research flow.

Identification of Risks

A comprehensive literature review was conducted using the Scopus search engine, which was selected for this study due to its accuracy and performance (Okudan et al., 2024). As a result of the extensive literature review, 21 risks were identified, and they are shown in Table 2.

Table 2. Extracted risks from the literature.

ID	Risk	References
PDR1	Risk of contractor compliance with legislation and policy	(Chang et al., 2010)
PDR2	Tight project schedule	(Chang et al., 2010)
PDR3	Contractor's competence in delivering fast-track reconstruction projects	(Chang et al., 2010)
PDR4	Cost and method of logistics due to simultaneous projects	(Chang et al., 2010)
PDR5	Turbulent macro environment	(Chang et al., 2010)
PDR6	Long lead time for procurement	(Chang et al., 2010)
PDR7	Failure to satisfy resilience requirements in design	(Charles et al., 2023)
PDR8	Lack of financing	(Charles et al., 2023)
PDR9	Inadequate Stakeholder communication	(Charles et al., 2023)
PDR10	Design incompatible with the culture of the region	(Charles et al., 2023)
PDR11	Failure to involve the community in the processes	(Charles et al., 2023)
PDR12	Labor shortage	(Mohammadnazari et al., 2022)
PDR13	Insufficient machinery and equipment	(Mohammadnazari et al., 2022)
PDR14	Material shortage	(Mohammadnazari et al., 2022)
PDR15	Inadequate qualification of staff	(Mohammadnazari et al., 2022)
PDR16	Inadequate occupational health and safety due to overcrowding	(Mohammadnazari et al., 2022)
PDR17	Ineffective use of natural resources	(Ismail et al., 2017)
PDR18	Information system inefficiency	(Aliakbarlou et al., 2017)
PDR19	Financial strength and stability of the contractor	(Aliakbarlou et al., 2017)
PDR20	Contractor performance	(Rad et al., 2022)
PDR21	Hazardous substances and unsafe environments	(Carrasco & O'Brien, 2023)
PDR22	Broken mental and physical health of the local employees	(Carrasco & O'Brien, 2023)
PDR23	Occurrence of secondary disasters during the reconstruction	Authors' Contribution
PDR24	Limited re-use and/or recycle of disaster waste in the reconstruction projects	Authors' Contribution

Assessment of Risks

Risk assessment is an important step for reasons such as preventing negative consequences, supporting decision-making processes, and maximizing resource use. In this study, the effects of risks on cost, time, and quality were analyzed, and risk ranking was carried out using the Fuzzy TOPSIS method. The experts completed the method questionnaire in person and online to apply the fuzzy TOPSIS method and evaluate the risks. The profiles of the experts are given in Table 3.

Table 3. Information on experts.

Expert ID	Personal Profession	Years of Experience	Education
E1	Academia	3	Civil Engineer
E2	Academia	3	Civil Engineer
E3	Technical Advisor to CEO	12	Civil Engineer-Mechanical Engineer
E4	Technical Office Engineer	5	Civil Engineer
E5	Procurement Engineer	2	Civil Engineer
E6	Academia	4	Civil Engineer
E7	Control Engineer	2	Civil Engineer
E8	Geotechnical Design Engineer	4	Civil Engineer

Fuzzy TOPSIS

The Fuzzy TOPSIS method was developed to find solutions to MCDM processes under uncertainty by utilizing the principles of the TOPSIS method The Fuzzy TOPSIS method ranks and evaluates alternatives according to their distance from positive and negative solutions (Zyoud et al., 2016). The steps of the Fuzzy TOPSIS method are as follows.

Step 1. Weighting of criteria: $\widetilde{w}_j$ corresponds to the weights of the identified risks on the time, quality and cost selection factors. Risks were assessed by experts on a scale of 1-7.

$$W = [\widetilde{w}_1 \widetilde{w}_2 - -\widetilde{w}_j - -\widetilde{w}_n] \qquad (1)$$

Step 2. Aggregation of group judgments: The aggregation of assessments is calculated as shown in equation 2.

$$\tilde{x}_{ij} = \frac{1}{K}[\tilde{x}_{ij}^1 + \tilde{x}_{ij}^2 + \cdots \tilde{x}_{ij}^K] \qquad (2)$$

Step 3. Aggregation of the decision matrix: The decision matrix is as in equation 3.

$$\widetilde{D} = \begin{bmatrix} \tilde{x}_{11} & \cdots & \tilde{x}_{11} \\ \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \cdots & \tilde{x}_{mn} \end{bmatrix} i = 1,2, \ldots., m; j = 1,2, \ldots.., n \qquad (3)$$

Step 4. Calculation of Normalized Fuzzy Decision Matrix: R˜is calculated via Equation (4) shown below. R˜ means the normalized decision matrix.

$$\tilde{R} = [r_{ij}]_{mxn}\ i = 1,2, \ldots..m; j = 1,2, \ldots..n. \qquad (4)$$

$$\tilde{r}_{ij}\left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}\frac{c_{ij}}{c_j^*}\right) and\ c_j^* = max_i\ c_{ij}\ (benefit\ criteria) \qquad (5)$$

Step 5. Weighted normalized fuzzy decision matrix: The weights of the evaluation criteria are multiplied by the normalized decision matrix to obtain a weighted normalized decision matrix.

$$\tilde{V} = [\tilde{v}_{ij}]_{mxn}\ i = 1,2, \dots..m; j = 1,2, \dots..n\ where\ \tilde{v}_{ij} = \tilde{r}_{ij}(.)W_j \tag{5}$$

Step 6. Definition of fuzzy PIS and fuzzy NIS: Fuzzy PIS and fuzzy NIS are defined by using Eq. (6).

$$\begin{aligned} A^{+} &= \{\tilde{v}_1^{+}, \tilde{v}_2^{+}, \tilde{v}_3^{+} \dots . \tilde{v}_j^{+}\} \\ A^{-} &= \{\tilde{v}_1^{-}, \tilde{v}_2^{-}, \tilde{v}_3^{-} \dots . \tilde{v}_j^{-}\} \end{aligned} \tag{6}$$

While $\tilde{v}_1^{+}$ equals to (1,1,1), $\tilde{v}_1^{-}$equals to (0,0,0)
Step 7. Calculating the distance of each alternative to the fuzzy PIS and fuzzy NIS: The distances to the fuzzy PIS and fuzzy NIS are calculated using equations (7) and (8).

$$\begin{aligned} d(\tilde{v}_{ij}, \tilde{v}_j^{+}) &= \sqrt{\frac{1}{3}[(\tilde{v}_{ija} - \tilde{v}_{ja}^{+})^2 + (\tilde{v}_{ijb} - \tilde{v}_{jb}^{+})^2 + (\widetilde{v}_{ijc} - \tilde{v}_{jc}^{+})^2]} \\ d(\tilde{v}_{ij}, \tilde{v}_j^{-}) &= \sqrt{\frac{1}{3}[(\tilde{v}_{ija} - \tilde{v}_{ja}^{-})^2 + (\tilde{v}_{ijb} - \tilde{v}_{jb}^{-})^2 + (\tilde{v}_{ijc} - \tilde{v}_{jc}^{-})^2]} \end{aligned} \tag{7}$$

$$\begin{aligned} d_i^{+} &= \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^{+}), i = 1,2,3, \dots m \\ d_i^{-} &= \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^{-}), i = 1,2,3, \dots m \end{aligned} \tag{8}$$

Step 8: Closeness coefficient (CC_i) of each alternative: $CC_{i,}$ (closeness coefficient) indicates the distances from fuzzy PIS and fuzzy NIS simultaneously.

$$CC_i = \frac{d_i^{-}}{d_i^{+} + d_i^{-}} \tag{9}$$

As a result of the application of Fuzzy TOPSIS, an assessment of risks was carried out and explained in the following section.

Results and Discussion of Finding

In this study, the effects of risks affecting post-disaster reconstruction projects on quality, time, and cost were analyzed, and the ranking of risks was carried out with Fuzzy TOPSIS. The results are given in Table 4. "Lack of financing (PDR8)", "Contractor performance (PDR20)," and "Occurrence of secondary disasters during reconstruction (PDR23)" were ranked as the top three risks, respectively.

Table 4. Fuzzy TOPSIS results.

ID	Risk	Closeness Coefficient (CC)	Ranking
PDR1	Risk of contractor compliance with legislation and policy	0,252	11
PDR2	Tight project schedule	0,262	5
PDR3	Contractor's competence in delivering fast-track reconstruction projects	0,261	6
PDR4	Cost and method of logistics due to simultaneous projects	0,250	12
PDR5	Turbulent macro environment	0,267	4
PDR6	Long lead time for procurement	0,216	22
PDR7	Failure to satisfy resilience requirements in design	0,248	13
PDR8	Lack of financing	0,284	1
PDR9	Inadequate Stakeholder communication	0,258	9
PDR10	Design incompatible with the culture of the region	0,200	24
PDR11	Failure to involve the community in the processes	0,230	19
PDR12	Labor shortage	0,226	20
PDR13	Insufficient machinery and equipment	0,224	21
PDR14	Material shortage	0,242	15
PDR15	Inadequate qualification of staff	0,256	10
PDR16	Inadequate occupational health and safety due to overcrowding	0,231	18
PDR17	Ineffective use of natural resources	0,240	16
PDR18	Information system inefficiency	0,212	23
PDR19	Financial strength and stability of the contractor	0,261	7
PDR20	Contractor performance	0,280	2
PDR21	Hazardous substances and unsafe environments	0,233	17
PDR22	Broken mental and physical health of the local employees	0,259	8
PDR23	Occurrence of secondary disasters during the reconstruction	0,279	3
PDR24	Limited re-use and/or recycle of disaster waste in the reconstruction projects	0,242	14

Post-disaster reconstruction projects are crucial for the normalization of a community that has been damaged by disasters. Disasters cause great damage to the economy by damaging income-generating sectors (Mannakkara et al., 2018). This problem, combined with the high investment potential required by post-disaster projects, can lead to a lack of financing. "Lack of financing" will negatively affect the realizability and delivery of projects. Therefore, allocating sufficient resources for reconstruction projects is a major challenge. Mohammadnazari et al. (2022) emphasized the importance of the lack of financing and stated that post-disaster reconstruction projects should be prioritized. This proves that lack of financing is a significant risk. Establishing an emergency fund as a solution to the lack of financing and developing public-private partnerships can be preventive for this significant risk. On the other hand, "Contractor performance (PDR20)" is another important risk in post-disaster reconstruction projects. Compared to traditional pre-disaster projects, contractors perform poorly in post-disaster projects (Mohammadnazari et al., 2022). Contractors need to perform positively in the uncertain post-disaster environment to deliver projects to the community on time and successfully. Since the risk of “Contractor's competence (PDR3)" may also affect contractor performance, selecting and monitoring contractors according to the relevant criteria after determining the competence and performance criteria in detail may benefit the successful delivery of the projects. Another risk factor that may affect the successful delivery of projects is the "occurrence of secondary disasters during reconstruction (PDR23)". On February 6, 2023, in the Kahramanmaraş earthquakes, a second strong earthquake occurred about 8 hours after the first earthquake. Aftershocks have also been ongoing for a long time (Agency 2023). For the sustainability of projects, the secondary disaster factor should be taken into consideration and necessary risk measures should be taken. Inadequate risk planning leads to a weak management system against unforeseen events and is an important factor in project failure (Hilu & Hiyassat, 2023).

Overall, the results will contribute to the post-disaster management literature and decision-makers in theoretical and practical terms. In light of the risks and their ranking given in Table 4, researchers and decision-makers will be able to better recognize the risks in post-disaster reconstruction projects and take necessary precautions. Thus, the successful delivery of post-disaster reconstruction projects to the community will be realized.

Conclusion

This study aims to identify and analyze the risks affecting post-disaster reconstruction projects and to introduce the risks to decision-makers in post-disaster reconstruction projects and researchers who want to conduct research in the literature and to shed light as a result of the analysis of risks. For this purpose, a comprehensive literature review was conducted and 24 risks were identified through literature review and author contributions. The identified risks and their impact on the time, quality, and cost criteria of the project and the evaluation of the risks were carried out with Fuzzy TOPSIS. According to the results of the analysis, "lack of financing", "contractor performance", "occurrence of secondary disasters" factors were ranked in the top three. Uncertainty and economic problems brought by the disaster will bring along lack of financing and will have a negative impact on the success of the project. On the other hand, criteria such as "performance of contractors" and "competence of contractors" rank high, proving that incorrect selection of a contractor can lead to significant risks. In addition, this study explains the need for risk management planning against the risk of "occurrence of secondary disasters". This study offers theoretical and practical contributions. There is no study in the literature that examines the risks affecting post-disaster reconstruction projects together and fills the gap in the literature. In post-disaster management planning, decision-makers can take into account the identified risks and realize risk response plans, which will ensure the successful delivery of projects. However, this study has some limitations. This study did not examine post-disaster reconstruction projects separately as superstructure or infrastructure. Future studies can be conducted to identify risks separately according to project types.

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References

Agency, A. (2023). *Turkish Presidency Strategy and Budgetary Office*. *March*, 6–7. https://www.sbb.gov.tr/wp-content/uploads/2023/03/2023-Kahramanmaras-and-Hatay-Earthquakes-Report.pdf

Aliakbarlou, S., Wilkinson, S., Costello, S. B., & Jang, H. (2017). Client values within post-disaster reconstruction contracting services. *Disaster Prevention and Management*, *26*(3), 348–360. https://doi.org/10.1108/DPM-03-2017-0058

Alizadeh, R., Gharizadeh Beiragh, R., Soltanisehat, L., Soltanzadeh, E., & Lund, P. D. (2020). Performance evaluation of complex electricity generation systems: A dynamic network-based data envelopment analysis approach. *Energy Economics*, *91*, 104894. https://doi.org/10.1016/j.eneco.2020.104894

Bahmani, H., & Zhang, W. (2022). A conceptual framework for integrated management of disasters recovery projects. *Natural Hazards*, *113*(2), 859–885. https://doi.org/10.1007/s11069-022-05328-5

Carrasco, S., & O'Brien, D. (2023). Build back safely: Evaluating the occupational health and safety in post-disaster reconstruction. *Sustainability (Switzerland)*, *15*(9). https://doi.org/10.3390/su15097721

Chang, Y., Wilkinson, S., Seville, E., & Potangaroa, R. (2010). Resourcing for a resilient post-disaster reconstruction environment. *International Journal of Disaster Resilience in the Built Environment*, *1*(1), 65–83. https://doi.org/10.1108/17595901011026481

Charles, S. H., Chang-Richards, A. Y., & Yiu, T. W. (2022). A systematic review of factors affecting post-disaster reconstruction projects resilience. *International Journal of Disaster Resilience in the Built Environment*, *13*(1), 113–132. https://doi.org/10.1108/IJDRBE-10-2020-0109

Charles, S. H., Chang-Richards, A., & Yiu, T. W. (2023). Providing a framework for post-disaster resilience factors in buildings and infrastructure from end-users' perspectives: case study in Caribbean island states. *International Journal of Disaster Resilience in the Built Environment*, *14*(3), 366–386. https://doi.org/10.1108/IJDRBE-02-2021-0020

Fayazi, M., & Lizarralde, G. (2018). Conflicts between recovery objectives: The case of housing reconstruction after the 2003 earthquake in Bam, Iran. *International Journal of Disaster Risk Reduction*, *27*(July 2017), 317–328. https://doi.org/10.1016/j.ijdrr.2017.10.017

Ghannad, P., Lee, Y.-C., Friedland, C. J., Choi, J. O., & Yang, E. (2020). Multiobjective optimization of postdisaster reconstruction processes for ensuring long-term socioeconomic benefits. *Journal of Management in Engineering*, *36*(4), 1–15. https://doi.org/10.1061/(asce)me.1943-5479.0000799

Hilu, K. A., & Hiyassat, M. A. (2023). Qualitative assessment of resilience in construction projects. *Construction Innovation*. https://doi.org/10.1108/CI-10-2022-0265

Hofmann, S. Z. (2022). Build back better and long-term housing recovery: Assessing community housing resilience and the role of insurance post disaster. *Sustainability (Switzerland)*, *14*(9). https://doi.org/10.3390/su14095623

Ismail, F. Z., Halog, A., & Smith, C. (2017). How sustainable is disaster resilience?: An overview of sustainable construction approach in post-disaster housing reconstruction. *International Journal of Disaster Resilience in the Built Environment*, *8*(5), 555–572. https://doi.org/10.1108/IJDRBE-07-2016-0028

Khasalamwa, S. (2009). Is “build back better” a response to vulnerability? Analysis of the post-tsunami humanitarian interventions in Sri Lanka. *Norsk Geografisk Tidsskrift*, *63*(1), 73–88. https://doi.org/10.1080/00291950802712152

Maly, E. (2018). Building back better with people centered housing recovery. *International Journal of Disaster Risk Reduction*, *29*, 84–93. https://doi.org/10.1016/j.ijdrr.2017.09.005

Mannakkara, S., & Wilkinson, S. (2013). Build back better principles for post-disaster structural improvements. *Structural Survey*, *31*(4), 314–327. https://doi.org/10.1108/SS-12-2012-0044

Mannakkara, S., & Wilkinson, S. (2014). Re-conceptualising “Building Back Better” to improve post-disaster recovery. *International Journal of Managing Projects in Business*, *7*(3), 327–341. https://doi.org/10.1108/IJMPB-10-2013-0054

Mannakkara, S., Wilkinson, S., & Potangaroa, R. (2018). Resilient post disaster recovery through building back better. In *Resilient Post Disaster Recovery through Building Back Better*. https://doi.org/10.1201/9781315099194

Mohammadnazari, Z., Mousapour Mamoudan, M., Alipour-Vaezi, M., Aghsami, A., Jolai, F., & Yazdani, M. (2022). Prioritizing post-disaster reconstruction projects using an integrated multi-criteria decision-making approach: A case study. *Buildings*, *12*(2), 1–26. https://doi.org/10.3390/buildings12020136

Okudan, O., Demirdöğen, G., & Işık, Z. (2024). A decision-support framework for suspension of public infrastructure projects: A combined use of neutrosophic AHP and TOPSIS. *Engineering, Construction and Architectural Management*. https://doi.org/10.1108/ECAM-08-2023-0795

Rad, M. H., Mojtahedi, M., Ostwald, M. J., & Wilkinson, S. (2022). A conceptual framework for implementing lean construction in infrastructure recovery projects. *Buildings*, *12*(3). https://doi.org/10.3390/buildings12030272

Remes, J., Gould, K., & Garcia, M. (2016). Beyond “natural-disasters-are-not-natural”: The work of state and nature after the 2010 earthquake in Chile. *Journal of Political Ecology*, *23*(1). https://doi.org/10.2458/v23i1.20181

RICS. (2006). *Mind the gap! Post-disaster reconstruction and the transition from humanitarian relief*. *June*, 1–105.

Saner, H. S., Yucesan, M., & Gul, M. (2022). A Bayesian BWM and VIKOR-based model for assessing hospital preparedness in the face of disasters. *Natural Hazards*, *111*(2). Springer Netherlands. https://doi.org/10.1007/s11069-021-05108-7

Sapeciay, Z., Wilkinson, S., & Costello, S. B. (2017). Building organisational resilience for the construction industry: New Zealand practitioners' perspective. *International Journal of Disaster Resilience in the Built Environment*, *8*(1), 98–108. https://doi.org/10.1108/IJDRBE-05-2016-0020

Siriwardhana, S. D., & Kulatunga, U. (2023). Evolution of post-disaster reconstruction policy framework in Sri Lanka: A longitudinal case study. *International Journal of Disaster Risk Reduction*, *85*(December 2022), 103506. https://doi.org/10.1016/j.ijdrr.2022.103506

Tavakoli Taba, S., Mojtahedi, M., & Newton, S. (2020). Disaster risk management approaches in construction and built environment: A research collaboration networks perspective. *International Journal of Disaster Resilience in the Built Environment*, *11*(1), 85–99. https://doi.org/10.1108/IJDRBE-06-2019-0032

Twigg, J. (2007). *Characteristics of a disaster-resilient community (Version 1 for Field Testing)*. *1*(August). https://practicalaction.org/docs/ia1/community-characteristics-en-lowres.pdf

UN Secretary-General. (2016). *Report of the open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction*. *21184*(December), 1–41.

Yang, J., & Cheng, Q. (2020). The impact of organisational resilience on construction project success: Evidence from large-scale construction in China. *Journal of Civil Engineering and Management*, *26*(8), 775–788. https://doi.org/10.3846/jcem.2020.13796

Zyoud, S. H., Kaufmann, L. G., Shaheen, H., Samhan, S., & Fuchs-Hanusch, D. (2016). A framework for water loss management in developing countries under fuzzy environment: Integration of Fuzzy AHP with Fuzzy TOPSIS. *Expert Systems with Applications*, *61*, 86–105. https://doi.org/10.1016/j.eswa.2016.05.016

Identifying Community Expectations in Post-Disaster Reconstruction Projects

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Abstract

The concept of Build Back Better has recently been widely used in the design and execution of post-disaster reconstruction projects. The build back better is the resilient-oriented approach that aims to enhance the resilience of communities to a level that is even higher than the pre-disaster term. In contrast to traditional approaches that are based only on the rapid replacement of damaged structural environments, the build back better approach also enhances the societal, economic, and environmental wellness of the communities. To achieve this, community expectations lie at the center of the build back better approach. Accordingly, this approach dictates that communities' expectations should be identified properly and post-disaster reconstruction projects should be designed and executed in a way that can satisfy these expectations. Although a plethora of studies related to post-disaster reconstruction projects were conducted in the literature, the community expectations in these projects are often neglected. To bridge this gap, this study aims to identify the community expectations in post-disaster reconstruction projects. Initially, an in-depth literature review was conducted to identify community expectations that are proposed by existing studies. Lastly, a questionnaire survey, DEMATEL method, and consistency analysis were conducted respectively to identify the weights of the identified expectations.

Keywords: *build back better, community, disaster, multi-criteria decision-making technique, post-disaster reconstruction.*

Introduction and Research Background

The frequency, magnitude, and severity of natural disasters such as earthquakes, hurricanes, and floods have recently skyrocketed, posing a significant threat to the economy, society, and built environment (Bahmani & Zhang, 2021). The recent disasters have revealed the vulnerability of the communities to natural disasters (Wei et al., 2021). Even, the critical public infrastructure of many countries failed to provide basic service to the affected people in the wake of natural disasters. For instance, the healthcare facilities failed to provide service to the affected people during extreme floods in Golestan, Iran, in 2019 (Anshuka et al., 2021). Similar incidents have also continuously occurred around the globe, such as the massive damage in the wake of the recent earthquake in Indonesia. The Türkiye is not an exemption. The recent earthquakes that occurred on February 6, 2023, in Türkiye, hit the southern cities and caused massive damage to the built environment (Agency, 2023).

These incidents revealed that it is a matter of life and death to built resilient cities to natural disasters. Furthermore, population growth and increasing demand for complex facilities and buildings maximize the direct and secondary impacts of natural disasters (Mohammadnazari et al., 2022). Consequently, various organizations and non-governmental organizations (NGOs) are warning to built resilient cities in both pre- and post-disaster periods. Otherwise, the detrimental impacts of natural disasters on the communities become inevitable and chronic.

Built back better concept has recently been a popular approach to build resilient cities, especially in the post-disaster period (Global Facillity for Disaster Reduction and Recovery, 2017). The concept was first coined by the United Nations in the aftermath of the 2004 Indian Ocean earthquake and tsunami (UN Secretary-General, 2016). By definition, the approach aims to minimize the vulnerability to future disasters by addressing physical, social, environmental, and economic vulnerabilities and shocks. The Built back better framework allows communities not only to recover from a current disaster but also to reduce the risks of future disasters. In this way, the approach becomes a proactive strategy to cope with future disasters. The concept involves efforts to improve land use, spatial planning, and construction standards through the entire life cycle of the reconstruction and recovery process. Community expectations also lie at the center of this concept. Accordingly, the entire built environment should be designed as in line with the expectations of the community. Otherwise, the social aspects of the reconstruction projects can hardly be satisfied.

MCDM techniques are the mathematical tool that enables decision-makers and/or researchers to assess the alternatives by considering conflicting decision-making criteria. The techniques become ideal when laboratory experiments and/or mathematical models can not be developed due to the huge amount of variables that exist in the nature of post-disaster reconstruction projects (Alipour-Vaezi et al., 2022). In a typical decision-making problem, the fundamental objective is to determine the final decision to be made. Thus, the MCDM methods such as DEMATEL was designed in a way that satisfy this objective. Looking into existing literature, although community expectations are must to ensure the success of post-reconstruction projects, there are limited studies devoted to this subject. Also, causal relationships of the community expectations have not been investigated, yet. Thus, this study aims fill this gap by identifying the community expectations together with their casual relationships.

The paper is structured as follows. The research gap analysis was presented in the following section to reveal the research gaps that exist in the literature. This was then followed by the methodology section which was devoted to methodology followed in this study. Lastly, sections 4 and 5 introduce the results and discussions of findings, and conclusions, respectively.

Research Gap Analysis

Looking into existing literature, very few studies focused on community expectations in post-reconstruction projects. The very first study was conducted by Aliakbarlou et al. (2017). The authors investigated and prioritized the key client values for the post-disaster reconstruction projects. The study adopted a literature review, semi-structured interviews, and a questionnaire survey as methodology. Accordingly, 39 client values were determined in the study. The results suggested that timeliness, availability of resources, competency, building a trust-based relationship, and financial stability were rated as the top factors. Maly (2018) conducted another study that focus on people centered housing recovery. By using the experience gathered from 2010 volcanic eruption of Mt. Merapi in Indonesia, and the 2013 Typhoon Yolanda in the

Philippines, the authors developed a decision-making framework. The framework focused on various aspects of the housing projects. There are housing designs and forms that meet people's needs; and genuine participation of empowered residents in decision-making and construction; and holistic policies accountable to all residents. The last study was conducted by Charles et al. (2023). The research aimed to determine the expectations for post-disaster reconstruction projects. Within the scope of the resarch, a systematic literature review was conducted to identify 24 factors. The relative significance of the factors was then assessed by conducting a questionnaire survey with the participation of end-users in the Caribbean. The results suggested that reconstruction designs mindful of future hazards, policies that aid climate change mitigation, active assessment of key structures.

Although various efforts have already been made to identify community expectations, the existing literature provided little knowledge about Türkiye. Given the fact that Türkiye has its inherent differences, the findings of the existing studies can barely be implemented in Türkiye. Furthermore, existing studies do not adopt an MCDM technique, undermining the reliability of the results significantly.

Research Methodology

In this study, a two-step methodology was applied to identify and assess community expectations in post-disaster reconstruction projects. Figure 1 shows the research methodology adopted in this study. A comprehensive literature review was initially applied to identify expectations. In the second step, a questionnaire survey and DEMATEL technique was jointly implemented to evaluate the causal relationships of expectation factors.

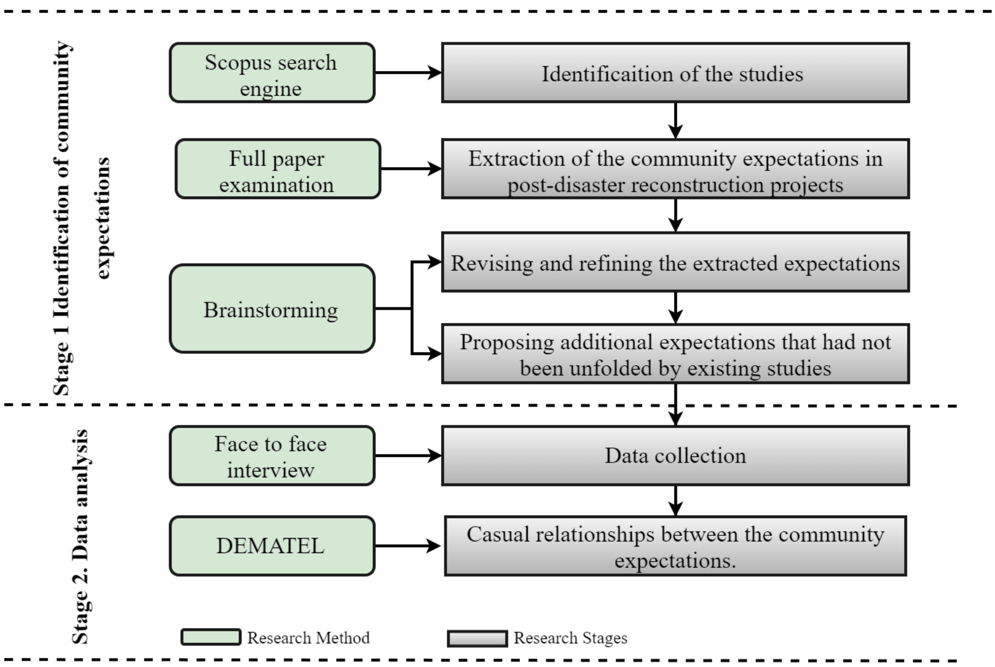

Figure 1: Research flow.

Identification of Expectation Factors

A comprehensive literature review and brainstorming were conducted to identify expectation factors, and the Scopus search engine was used in the literature review. Scopus search engine was preferred due to its popularity, reliability, and comprehensiveness (Okudan & Çevikbaş, 2022). As a result of a comprehensive literature review and brainstorming, 10 expectation factors were identified and shown in Table 1.

Table 1. Expectation factors.

ID	Expectation Factor	References
F1	Location of the Project (Distance to facilities and services, distance to transportation systems)	(Xiang et al., 2018)
F2	Realization of architectural design by preserving the historical atmosphere and preserving the social environment in accordance with the local culture	(Xiang et al., 2018), Authors contribution
F3	Delivery of the project quickly and with quality standards	(Aliakbarlou et al., 2017; Xiang et al., 2018)
F4	Working with Competent Contractors	(Rad et al., 2022)
F5	Community involvement in project processes and trust-based stakeholder relations	(Aliakbarlou et al., 2017; Xiang et al., 2018)
F6	Preventing loss of rights and providing the necessary assurances after project delivery	(Aliakbarlou et al., 2017), Authors contribution
F7	Including social facilities in projects	Authors contribution
F8	Protection of the natural environment during construction	(Aliakbarlou et al., 2018)
F9	Creation of employment through the project	(Mohammadnazari et al., 2022)
F10	Reasonable payment plan	Authors contribution

Assessment of Expectation Factors

It is important to identify and assess the expectations of the community after the disaster because of the great damage to the community and to make the community better than it was before. In this section, we go beyond the traditional MCDM ranking logic for the evaluation of factors and aim to find the root factors by evaluating the effects of factors on each other. For this purpose, the DEMATEL method was used to evaluate the factors. For the realization of the DEMATEL method, a questionnaire was created, and the survey was conducted by 9 members of the community who had suffered a disaster.

DEMATEL

The DEMATEL method was first developed between 1972 and 1976 by the Science and Human Affairs Program of the Battelle Memorial Institute of Geneva to study complex and interconnected problems (Shieh et al., 2010). The method applies a structural modeling approach based on analysis by graph theory and visualization. This approach adopts the causal effect diagram to present the interdependence between factors and the amount of effect (Lin, 2013). Through this graph, factors are grouped into cause factors and effect factors. This provides a better understanding of the relationships between factors and allows complex problems to be solved (Lin, 2013). This distinguishes it from the traditional AHP method (Shieh et al., 2010). The calculation steps of the DEMATEL method are as follows (Costa et al., 2019).

Step 1. Development of the Average Decision Matrix: To investigate the relationship between factors in a list of n factors, an n x n matrix is created. The influence of factors on each other is scored as 0, 1, 2, 3, and 4 and corresponds to "no influence," low influence," moderate influence," strong influence," and "very strong influence," respectively. The matrix averaging the scores of the participants is the average decision matrix and is denoted by $\boldsymbol{Z}$.

Step 2. Normalization of The Decision Matrix: The normalized matrix ($\boldsymbol{X}$) is generated as in the formula.

$$S = max(\sum_{j=1}^{n} Z_{ij}, \sum_{i=1}^{n} Z_{ij}) \qquad (1)$$

$$\boldsymbol{X} = \frac{\boldsymbol{Z}}{S} \qquad (2)$$

Step 3. Generation of the Total Relationship Matrix: The total relationship matrix (T) is created with the following formulation.

$$\boldsymbol{T} = \sum_{q=1}^{\infty} \boldsymbol{X}^{i} = \boldsymbol{X}+\boldsymbol{X}^{2}+\boldsymbol{X}^{3} + \cdots + \boldsymbol{X}^{q} = \frac{\boldsymbol{X}(\boldsymbol{I}-\boldsymbol{X}^{q})}{(\boldsymbol{I}-\boldsymbol{X})}$$

$$= \frac{\boldsymbol{X}(\boldsymbol{I}-\boldsymbol{X}^{\infty})}{(\boldsymbol{I}-\boldsymbol{X})} = \frac{\boldsymbol{X}}{(\boldsymbol{I}-\boldsymbol{X})} = (\boldsymbol{XI}-\boldsymbol{X})^{-1} \qquad (3)$$

Step 4. Calculation of Prominence and Relevance Values: The sums of each row (*Ri*) and column (*Dj*) are determined separately from the total relationship matrix (T).

$$Dj = \sum_{j=1}^{n} t_{ij} \ \forall \boldsymbol{j} \qquad Ri = \sum_{j=1}^{n} t_{ij} \ \forall \boldsymbol{j} \quad (4)$$

Ri indicates the effect of factor i on other factors, while *Dj* indicates the effect of factor j on other factors.

For each factor, prominence (*Pi*) and net effect (*Ei*) are determined. The formulations are as follows.

$$Pi = \{Ri + Dj \mid i = j\} \qquad (5)$$

$$Ei = \{Ri - Dj \mid i = j\} \qquad (6)$$

The larger the *Pi* value, the greater the influence/importance of factor i in terms of its relationship with other factors. If *Ei* is greater than 0, it is an effector and if it is less than 0, it is an affected factor.

Step 5. Drawing the Cause - Effect Diagram and Setting the Threshold Value

Since the T matrix shows how one factor affects the other, a threshold value must be determined to neglect some negligible effects when analyzing the factors. After determining the threshold value, values greater than it will be selected and shown in the diagram. The threshold is determined by the sum of the mean and standard deviation of the T matrix (Costa et al., 2019).

Based on the mentioned steps, the DEMATEL method was applied to the factors, and the results are given in the next section.

Results and Discussion of Finding

Table 2 shows the results of the analysis of community expectations with DEMATEL, and Figure 2 shows the Cause-Effect diagram.

Table 2. DEMATEL results.

ID	Rank in DEMATEL	Net Effect	Prominence	Causal Position	Effect on	Effect by
F1	2	0,56	9,25	Net Cause	F3, F8	-
F2	5	0,36	9,59	Net Cause	F3, F4, F8	F4
F3	9	-0,95	9,96	Net Effect	-	F1, F2, F4, F5, F7, F10
F4	4	0,38	9,97	Net Cause	F2, F3, F6, F8, F10	F2, F5
F5	1	0,71	9,47	Net Cause	F3, F4, F6, F8	-
F6	8	-0,33	8,32	Net Effect	-	F4, F5
F7	3	0,56	8,99	Net Cause	F3	-
F8	10	-1,14	8,41	Net Effect	-	F1, F2, F4, F5
F9	6	0,08	7,71	Net Cause	-	-
F10	7	-0,24	8,84	Net Effect	F3	F4

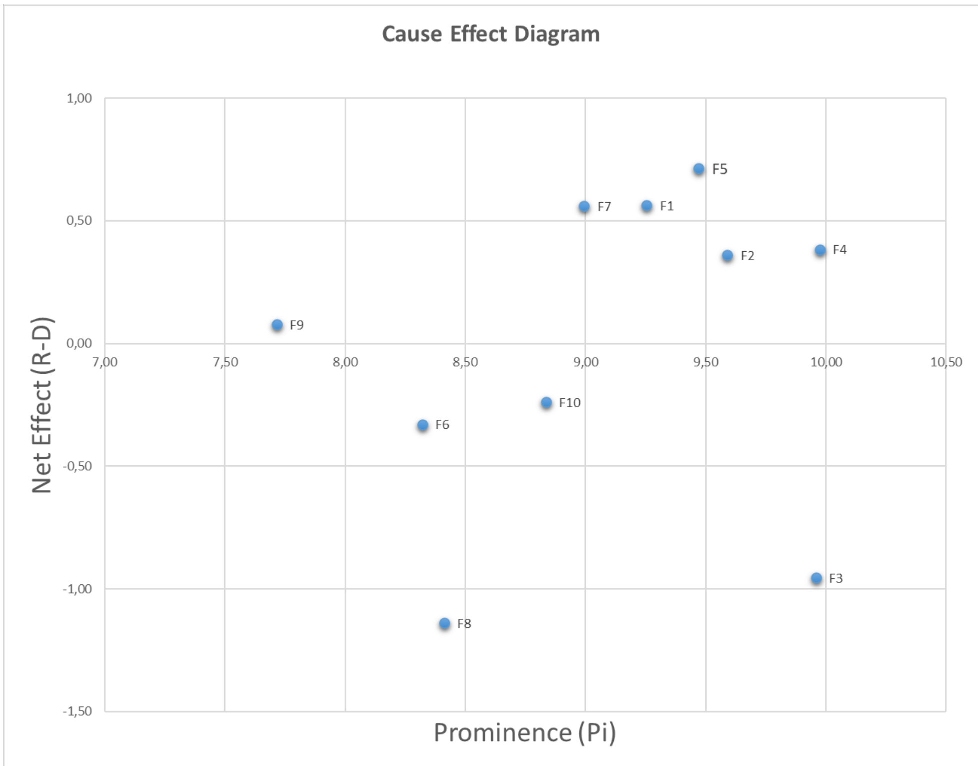

Figure 2: Casual effect diagram.

According to the results of the analysis, F5 (Community involvement in project processes and trust-based stakeholder relations), F1 (Location of the Project (Distance to facilities and services, distance to transportation systems), F7 (Including social facilities in projects), F4 (Working with Competent Contractors), F2 (Realization of architectural design by preserving the historical atmosphere and preserving the social environment in accordance with the local culture) come to the prominence as the factors that predominantly affect the other factors. Community participation in project processes and a trust-based stakeholder relations (F5) is an important factor for community redevelopment in post-disaster reconstruction projects. The results show that the realization or planning of the realization of this factor, working with competent contractors, can have an impact on the successful delivery of the project, avoiding loss of rights and protecting the natural environment during construction. This is because factor F5 requires selecting contractors with a history of managing successful stakeholder relationships, which can increase competence. In addition, the involvement of the community in the processes can prevent potential conflicts and thus prevent loss of rights. Moreover, the involvement of the community in the project processes and the importance given by the community to the natural environment can ensure the protection of the natural environment. The project location factor (F1) is one of the factors affecting some of the expectation factors. Incorrect selection of the location of the project may prolong the construction period and cause extra costs due to physical problems that may be encountered. This will affect the speed and quality standards of delivery of the project. In addition, the location of the project has an impact on the protection of the natural environment during construction, as the construction of the project in a region with a lot of natural diversity may damage the natural environment.

Working with competent contractors (F4) is another important factor and the factor that affects the most factors in terms of number. According to the results, a competent contractor has an impact on the preservation of the historical atmosphere and the construction of buildings in accordance with the local culture, the successful delivery of the project, the prevention of loss of rights, the protection of the natural environment during construction and reasonable payment plans. This shows that working with a competent contractor has an important share in meeting most of the expectations of the community.

Moreover, this study contains important findings that can help meet the community's expectations in post-disaster reconstruction projects by identifying their expectations and analysing their impact on each other.

Conclusion

This study was developed to help decision-makers take action to meet community expectations in post-disaster reconstruction projects by identifying and analysing community expectations in post-disaster reconstruction projects. In the first step, a comprehensive literature review was conducted, and 10 expectation factors were identified in the light of the literature review and through brainstorming. Unlike traditional pairwise comparison methods, cause-effect analysis was performed with DEMATEL to find the root cause and to help meet expectations in an optimum way. According to the results, F5 (Community involvement in project processes and trust-based stakeholder relations), F1 (Location of the Project (Distance to facilities and services, distance to transportation systems), F7 (Including social facilities in projects), F4 (Working with Competent Contractors), F2 (Realization of architectural design by preserving the historical atmosphere and preserving the social environment in accordance with the local culture) have come to the fore as factors affecting other factors. Although F5 ranks first in the net effect ranking, F4 (the factor of working with competent contractors) is the leading factor in terms of the number of factors it affects.

This study is the first theoretical attempt to analyze community expectations in post-disaster reconstruction projects by bringing together various literature and conducting cause-effect analysis. In practical terms, it will help decision-makers to take action to meet the expectations of the community in the reconstruction process. In addition, this study contributes to the principle by putting community at the center of the project as in the build-back better principle. The study has several limitations. The factors were developed from the literature and brainstorming by the authors. In addition, a limited number of community members could be surveyed during the analysis. Future studies can conduct a more comprehensive study in determining expectations and collecting analysis data.

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References

Agency, A. (2023). *Turkish Presidency Strategy and Budgetary Office*. *March*, 6–7. https://www.sbb.gov.tr/wp-content/uploads/2023/03/2023-Kahramanmaras-and-Hatay-Earthquakes-Report.pdf

Aliakbarlou, S., Wilkinson, S., Costello, S. B., & Jang, H. (2017). Client values within post-disaster reconstruction contracting services. *Disaster Prevention and Management*, *26*(3), 348–360. https://doi.org/10.1108/DPM-03-2017-0058

Aliakbarlou, S., Wilkinson, S., Costello, S. B., & Jang, H. (2018). Achieving postdisaster reconstruction success based on satisfactory delivery of client values within contractors' services. *Journal of Management in Engineering*, *34*(2), 1–12. https://doi.org/10.1061/(asce)me.1943-5479.0000581

Alipour-Vaezi, M., Aghsami, A., & Rabbani, M. (2022). Introducing a novel revenue-sharing contract in media supply chain management using data mining and multi-criteria decision-making methods. *Soft Computing*, *26*(6), 2883–2900. https://doi.org/10.1007/s00500-021-06609-0

Anshuka, A., van Ogtrop, F. F., Sanderson, D., Thomas, E., & Neef, A. (2021). Vulnerabilities shape risk perception and influence adaptive strategies to hydro-meteorological hazards: A case study of Indo-Fijian farming communities. *International Journal of Disaster Risk Reduction*, *62*, 102401. https://doi.org/10.1016/j.ijdrr.2021.102401

Bahmani, H., & Zhang, W. (2021). Comprehensive success evaluation framework for socio-natural disaster recovery projects. *Buildings*, *11*(12), 647. https://doi.org/10.3390/buildings11120647

Charles, S. H., Chang-Richards, A., & Yiu, T. W. (2023). Providing a framework for post-disaster resilience factors in buildings and infrastructure from end-users' perspectives: Case study in Caribbean island states. *International Journal of Disaster Resilience in the Built Environment*, *14*(3), 366–386. https://doi.org/10.1108/IJDRBE-02-2021-0020

Costa, F., Denis Granja, A., Fregola, A., Picchi, F., & Portioli Staudacher, A. (2019). Understanding relative importance of barriers to improving the customer–supplier relationship within construction supply chains using DEMATEL technique. *Journal of Management in Engineering*, *35*(3), 1–13. https://doi.org/10.1061/(asce)me.1943-5479.0000680

Global Facillity for Disaster Reduction and Recovery. (2017). *Building back better in post-disaster recovery*.

Lin, R. J. (2013). Using fuzzy DEMATEL to evaluate the green supply chain management practices. *Journal of Cleaner Production*, *40*, 32–39. https://doi.org/10.1016/j.jclepro.2011.06.010

Maly, E. (2018). Building back better with people centered housing recovery. *International Journal of Disaster Risk Reduction*, *29*(August 2017), 84–93. https://doi.org/10.1016/j.ijdrr.2017.09.005

Mohammadnazari, Z., Mousapour Mamoudan, M., Alipour-Vaezi, M., Aghsami, A., Jolai, F., & Yazdani, M. (2022). Prioritizing post-disaster reconstruction projects using an integrated multi-criteria decision-making approach: A case study. *Buildings*, *12*(2), 1–26. https://doi.org/10.3390/buildings12020136

Okudan, O., & Çevikbaş, M. (2022). Alternative dispute resolution selection framework to settle disputes in public–private partnership projects. *Journal of Construction Engineering and Management*, *148*(9), 1–17. https://doi.org/10.1061/(asce)co.1943-7862.0002351

Rad, M. H., Mojtahedi, M., Ostwald, M. J., & Wilkinson, S. (2022). A conceptual framework for implementing lean construction in infrastructure recovery projects. *Buildings*, *12*(3). https://doi.org/10.3390/buildings12030272

Shieh, J. I., Wu, H. H., & Huang, K. K. (2010). A DEMATEL method in identifying key success factors of hospital service quality. *Knowledge-Based Systems*, *23*(3), 277–282. https://doi.org/10.1016/j.knosys.2010.01.013

UN Secretary-General. (2016). *Report of the open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction*. *21184*(December), 1–41.

Wei, W., Mojtahedi, M., Yazdani, M., & Kabirifar, K. (2021). The alignment of Australia's national construction code and the Sendai framework for disaster risk reduction in achieving resilient buildings and communities. *Buildings*, *11*(10), 429. https://doi.org/10.3390/buildings11100429

Xiang, M., Zhao, W., & Chen, J. (2018). A comparison of different reconstruction modes and adaptive evaluation systems for community recovery following theWenchuan Earthquake. *Sustainability (Switzerland)*, *10*(11). https://doi.org/10.3390/su10114115

Corporate Universities in Construction Companies in Turkiye

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Abstract

A corporate university (CU) is "a centralized in-house training and education facility to address the shortened shelf life of knowledge and to align training and development with business strategies". It is one of the tools that companies use to address the challenges they face in managing change, surviving, competing, and thriving in a knowledge-based economy. While some construction companies have attempted to set up and run CUs, academic research on the construction industry has rarely addressed the CU concept and related components. In this paper, the researchers examine the current situation of CUs in construction companies based in Turkiye. To assess the current situation, internet research was conducted to analyze the current information through the websites of the 126 members of the Turkish Contractors Association. A similar study was conducted in the U.S., and the results showed, among many findings, that building construction companies tend to invest in CUs. This paper will present the findings of the current situation in Turkiye and discuss the main differences or similarities with the situation in the U.S.

Keywords: *construction companies, corporate universities, Turkiye.*

Introduction

Corporate Universities (CUs) represent a multifaceted concept. CUs have emerged as strategic assets for organizations, offering structured educational programs aimed at enhancing workforce capabilities, fostering innovation, and driving organizational change. The rise of a knowledge-driven economy requires businesses to continuously adapt. CUs are increasingly utilized by companies to maintain competitiveness as knowledge rapidly becomes outdated in various industries (Rademakers, 2005; Singh et al., 2020). Several factors contribute to this increase including rapid technological advancement necessitating skill updates (Rhéaume &

Gardoni, 2015; Singh et al., 2020), skill gaps in the labor force (Kolo et al., 2013; Chen et al., 2019), and the need to meet the expectations of a highly skilled workforce (Scarso, 2017).

CUs are present in various industries (Lui Abel & Li, 2012), and their prevalence and characteristics vary depending on the industry and geographical region. While various studies relate to CUs, their presence, specifically within the construction industry remains relatively understudied. This study aims to assess the current situation of CUs and related components in construction companies operating in Turkiye and to compare the situation in Turkiye with the situation in the U.S.

To achieve this aim, the websites of building construction companies that are members of the Turkish Contractors Association are analyzed. By examining the publicly available information in these websites, the existence of CUs and in-house education and training activities in Turkish construction companies is confirmed or refuted. In addition, the findings are compared with those of a previous study conducted in the U.S., where a similar methodology was employed, focusing on companies listed in the Engineering News-Record (ENR) Top 400 Contractors (ENR, 2022).

This study represents the first effort in Turkiye to investigate the concept/implementation of CUs in Turkish construction companies. The findings obtained from this research provide valuable insights to researchers, educators, and professionals in the construction management field by shedding light on the concept of CU, its related components, and opportunities for future research.

Literature Review

The concept of Corporate Universities (CUs) has evolved over time and has been investigated from various perspectives. The literature on CUs reflects this diversity, with different definitions (Alagaraja & Li, 2015) . While definitions of a CU emphasize their association with organizational objectives, there are nuances in how CUs are conceptualized from business, learning, and knowledge management perspectives (Singh et al., 2020). CUs are often depicted not solely as physical entities but also as overarching phenomena, concepts, or processes in the literature (Allen, 2002).

Discussions comparing CUs to Traditional Universities (TUs) underscore the distinctive features and purposes of each. A CU represents the process of structured internal training and corporate learning, but the appropriateness of the term "university" can be debated (Rhéaume & Gardoni, 2015). While some argue that CUs complement TUs by addressing specific organizational needs (Blass, 2005), concerns have been raised about the potential threats CUs pose to TUs (e.g., Nixon & Helms, 2002). However, CUs and TUs serve different functions and are not necessarily in direct competition (Blass, 2001).

The evolution of CUs reflects a transition from traditional training programs to more holistic approaches aimed at organizational learning and development. Walton (2005) outlines the evolution of CUs across three generations. The first generation essentially rebranded traditional training programs, prioritizing the teaching and promotion of corporate values. The second generation broadened its focus to organizational learning but was still tied to physical locations. In contrast, the current third generation integrates virtual learning components and offers a wide array of strategies for intellectual capital development. Currently, the role of technology in CUs has become increasingly prominent, facilitating digitization and personalized learning experiences (Singh et al., 2020).

Conceptualizing CU models presents a complex challenge, with scholars proposing various frameworks and building blocks to guide organizational initiatives. Prince and Stewart (2002) propose a comprehensive model encompassing knowledge systems, learning processes, network partnerships, and human resource processes. Kolo et al. (2013) outline key building blocks for successful CUs, including clear objectives, target audiences, content (offerings), delivery methods, and infrastructure components such as structure, collaboration, and so on. Despite a general framework, CUs are viewed as strategic tools tailored to the unique needs of each organization (Rhéaume & Gardoni, 2015).

Method

The study aimed to evaluate the situation of CUs in construction companies in Turkiye. To ensure a comprehensive representation of the construction landscape in Turkiye, the websites of the 126 members of the Turkish Contractors Association were analyzed. To narrow the focus of the study on building construction projects, 30 out of the 126 companies were excluded as these 30 companies did not undertake building projects. As a result, the study included a sample of 96 construction firms actively engaged in building construction activities.

The data collection process involved thoroughly examining the websites of the 96 building construction companies. This examination extended across all tabs on these companies' websites, as a dedicated tab about CUs or education and training activities was only rarely available.

The data collected include information on the presence of a CU, the availability of in-house education and training activities, the types of courses offered, the delivery methods, and collaborative initiatives. Numerical summaries of the collected data were compiled about the frequency of CUs, in-house education/training activities, and associated components for further analysis and discussion.

Findings and Discussion

This study examines the current state of corporate universities (CUs) in building construction companies in Turkiye. The membership list of the Turkish Contractors Association was used in the study. It was found that 30 out of the 126 members of the Turkish Contractors Association undertook exclusively infrastructure and/or industrial works and were therefore excluded from the sample used for the study reducing the size of the sample to a total of 96 building construction companies. As shown in Figure 1, the research indicated that 24 of the 96 companies (25%) offered in-house education and training activities.

A study conducted in the U.S. revealed that 102 out of 323 building construction companies (32%) provided in-house education and training programs to their employees (see Dogan et al., 2024). This agreement between the studies in Turkiye and in the U.S. underscores the importance of employee development in the construction sector, highlighting a shared commitment to nurturing talent and improving workforce capabilities. This approach fosters a culture of continuous learning and innovation among employees by enhancing their skill sets proactively.

Out of the 24 Turkish building construction companies providing education/training activities, 7 describe themselves as "academies." In Turkiye, the term "university" is not used for CUs, as per the policies and practices of the Higher Education Council. Conversely, the study conducted in the U.S. shows that construction companies have the flexibility to use both terms.

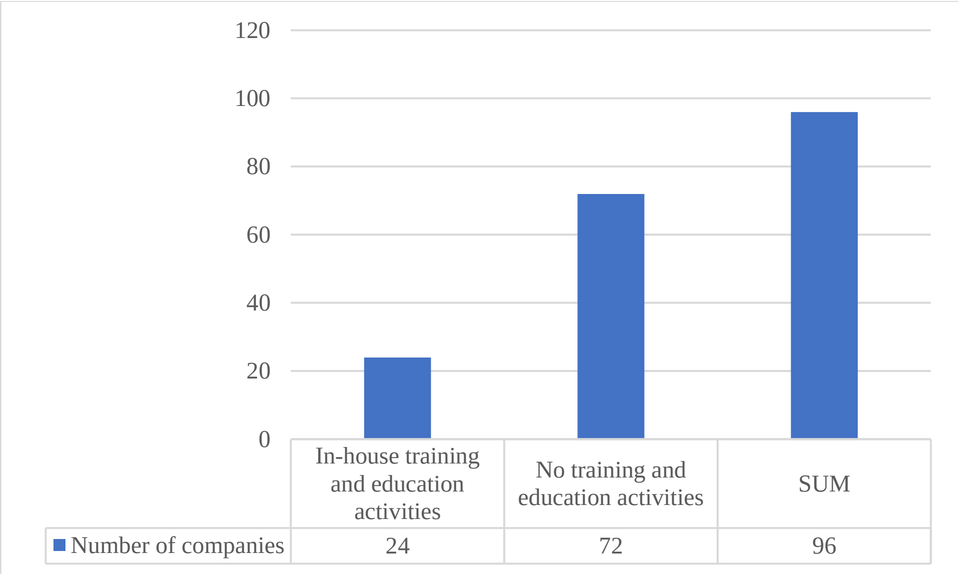

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Figure 1: Distribution of building construction companies with and without in-house education and training activities.

This study highlights that one out of every four building construction companies that are members of the Turkish Contractors Association provides in-house education and training programs. Notably, among these 24 firms, 13 are listed in ENR's Top 250 International Contractors (ENR, 2023). The observation that more than half of the 24-company sample of Turkish building construction companies extracted from ENR's Top 250 International Contractors (ENR, 2023) are offering in-house education and training activities suggests that CUs might serve as a strategic tool in larger Turkish building construction companies for enhancing global competitive advantage. Similarly, it was found that 32% of the American building construction companies extracted from ENR's Top 400 Contractors (ENR, 2022) are offering in-house education and training activities, which suggests that CUs might serve as a strategic tool in larger American building construction companies for enhancing local competitive advantage (Dogan et al., 2024).

This study also provides information on courses offered by 24 companies and their delivery methods. The most frequently offered courses in the 24 companies that provide education and training activities are personal development and leadership courses, which are offered in 9 and 8 companies, respectively (see Figure 2). These courses are followed by management and professional development courses in 7 out of the 24 companies.

According to both studies conducted in Turkiye and the U.S. (Dogan et al., 2024), developing leadership skills in professionals is an important function of CUs. Leadership-related courses emerge as the most frequently offered courses in Turkiye and the U.S., indicating a shared recognition of the importance of cultivating leadership skills in professionals employed in the building construction industry. This finding aligns with Kolo et al.'s (2013) assertion that developing leadership skills in professionals is the central focus of CUs regardless of industry.

It should be noted that the study conducted in the U.S. (Dogan et al., 2024) specifically highlights a focus on safety and health-related courses following leadership courses offered in building construction companies, whereas this is rarely mentioned in the websites of Turkish building construction companies (only 2 of the 24 companies). The difference between American and Turkish companies in this matter may be due to variations in regulations, cultural attitudes, or industry priorities.

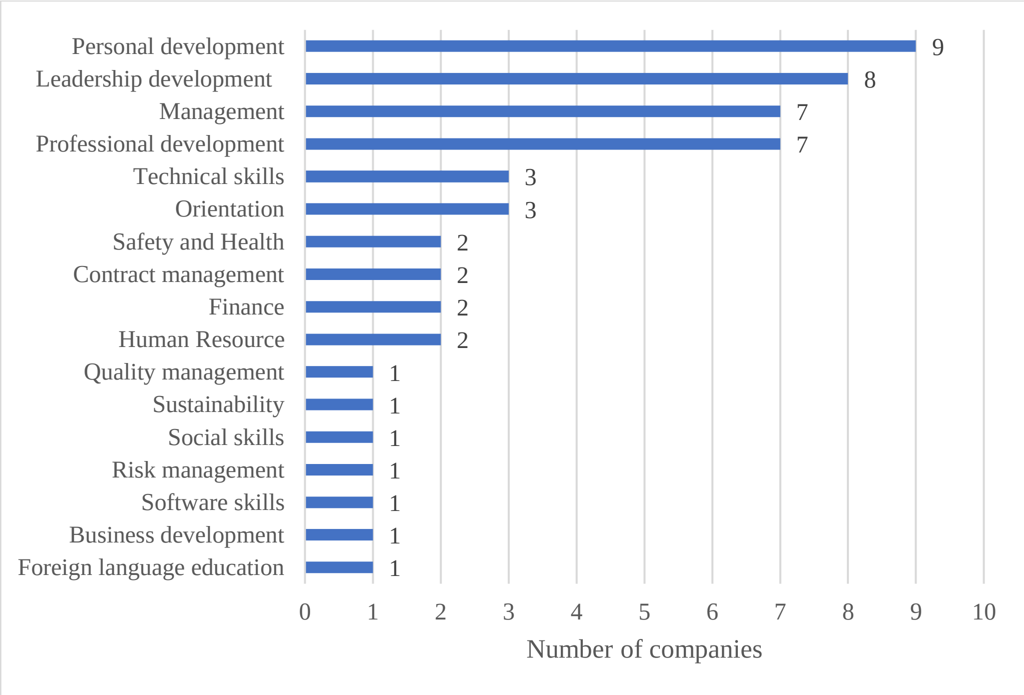

Figure 2: Course offerings.

The websites of Turkish building construction companies lack comprehensive and detailed information concerning the delivery methods of the courses offered. While traditional in-person classroom delivery and online methods are not explicitly highlighted, mentoring emerges as a common method of training/educating professionals, cited by 3 out of the 24 companies. This is followed by a rotation of professionals between different positions, noted by two companies, and seminars and conferences, also noted by two companies. This finding suggests that non-traditional strategies may be adopted in some Turkish construction companies to promote exposure to different disciplines and to facilitate career advancement.

Only 3 of the 24 companies that provide education and training activities collaborate with external entities like TUs or consultants. Furthermore, 4 of the 24 companies note that they offer both in-house and external training opportunities. Similarly, the U.S. study revealed that only 17 of the 102 companies collaborated with external entities, including TUs, training consultants, and professional associations. Both studies conducted in Turkiye and in the U.S. reveal a limited level of collaboration with external entities such as TUs, consultants, or professional associations. This finding suggests that the executives of Turkish and American building construction companies may not have fully grasped the potential benefits of collaborating with external entities to deliver CU-related activities. This finding underscores the need for increased awareness, incentives, and support to foster stronger collaboration between companies and TUs, external consultants, professional associations, and other such entities. By promoting knowledge exchange, mutual learning, and resource sharing between these parties, education and training efforts in the building construction industry can be significantly enhanced.

Conclusion

This study evaluates the current state of CUs in building construction companies in Turkiye. It shows that some companies are providing education and training activities to their employees through internal organizations that can be called CUs but are generally called "academies". Out of the 96 companies involved in building construction projects on the list of members of the Turkish Contractors Association, 24 companies (25%) provide in-house education and training activities. Although these initiatives may not have reached a high level of maturity, there are some efforts to develop better organized and more comprehensive activities even though CUs in Turkish building construction companies are not as formal and common as those in building construction companies in the U.S., with Turkish companies displaying less public information about education/training on their websites compared to the websites of their American counterparts.

The construction industry seems to be lagging behind other industries in developing and managing CUs. While successful and well-organized CUs are commonplace in various industries such as technology, finance, and automotive, it is rare to see a notable model in the building construction industry. However, workforce development is increasingly important in this rapidly changing work environment, where business practices are rarely stable and uniform. CUs can offer holistic solutions to building construction companies in this regard.

This study has two limitations. Firstly, it relies only on information that is publicly available on company websites. Due to the limited information available on company websites, some details may be inaccessible or overlooked. A follow-up study that involves a systemtic collection of information from professionals in the industry could shed light on issues that could not be investigated only by examining website contents. Secondly, the study focuses only on specific components, such as education and training activities and infrastructure, while disregarding other significant factors like the organization's objectives and framework. Future studies should consider a broader range of organizational elements, such as mission and goals, governance, structure, and digitization attempts, to gain a more comprehensive understanding of CUs.

References

Alagaraja, M., & Li, J. (2015). Utilizing institutional perspectives to investigate the emergence, rise, and (relative) decline of corporate universities. *Human Resource Development International*, *18*(1), 4–23. https://doi.org/10.1080/13678868.2014.979003

Allen, M. (2002). *I Introduction What is a corporate university, and why should an organization have one?* http://ebookcentral.proquest.com/lib/itup/detail.action?docID=1638695

Blass, E. (2001). *What's in a name? A comparative study of the traditional public university and the corporate university*. http://www.tandf.co.uk/journals

Blass, E. (2005). The rise and rise of the corporate university. *Journal of European Industrial Training*, *29*(1 SPEC. ISS.), 58–74. https://doi.org/10.1108/03090590510576217

Chen, Y., Xu, Y., & Zhai, Q. (2019). The knowledge management functions of corporate university and their evolution: case studies of two Chinese corporate universities. *Journal of Knowledge Management*, *23*(10), 2086–2112. https://doi.org/10.1108/JKM-04-2018-0228

Dogan, Y. O., Arditi, D., & Irlayıcı Cakmak, P. (2024). Corporate universities in building construction companies: Evidence from the U.S. Submitted for publication (under review).

Engineering News-Record. (2022, May). *ENR 2022 Top 400 Contractors*. ENR. https://www.enr.com/toplists/2022-Top-400-Contractors-1-preview

Engineering News-Record. (2023). *ENR 2023 Top 250 International Contractors*. ENR. https://www.enr.com/toplists/2023-Top-250-International-Contractors-Preview

Kolo, P., Strack, R., Cavat, P., Torres, R., & Bhalla, V. (2013). *Corporate universities: An engine for human capital*. https://www.bcg.com/publications/2013/people-organization-corporate-universities-engine-human-capital

Lui Abel, A., & Li, J. (2012). Exploring the corporate university phenomenon: Development and implementation of a comprehensive survey. *Human Resource Development Quarterly*, *23*(1), 103–126. https://doi.org/10.1002/hrdq.21122

Nixon, J. C., & Helms, M. M. (2002). Corporate universities vs higher education institutions. In *Industrial and Commercial Training*, *34*(4), (pp. 144-150). https://doi.org/10.1108/00197850210429129

Prince, C., & Stewart, J. (2002). Corporate universities – an analytical framework. *Journal of Management Development*, *21*(10), 794–811. https://doi.org/10.1108/02621710210448057

Rademakers, M. (2005). Corporate universities: Driving force of knowledge innovation. In *Journal of Workplace Learning*, *17*(1–2), (pp. 130–136). https://doi.org/10.1108/13665620510574513

Rhéaume, L., & Gardoni, M. (2015). The challenges facing corporate universities in dealing with open innovation. *Journal of Workplace Learning*, *27*(4), 315–328. https://doi.org/10.1108/JWL-03-2014-0023

Scarso, E. (2017). Corporate universities as knowledge management tools. *VINE Journal of Information and Knowledge Management Systems*, *47*(4), 538–554. https://doi.org/10.1108/VJIKMS-12-2016-0074

Singh, V., Verma, S., & Chaurasia, S. S. (2020). Mapping the themes and intellectual structure of corporate university: co-citation and cluster analyses. *Scientometrics*, *122*(3), 1275–1302. https://doi.org/10.1007/s11192-019-03328-0

Walton, J. (2005). Would the real corporate university please stand up? *Journal of European Industrial Training*, *29*(1), 7–20. https://doi.org/10.1108/03090590510576181

Agile Methodologies in Construction Management: A Review Study on Scrum and Kanban

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Abstract

The construction sector plays a vital role in driving the nation's development, constantly evolving to tackle projects ranging from intricate renovations to colossal infrastructure developments. However, this dynamism presents challenges. As projects become increasingly complex and client expectations for efficiency and sustainability rise, traditional project management approaches may struggle to adapt. Agile methodologies, renowned for their emphasis on flexibility, collaboration, and continuous improvement, offer a promising solution. Accordingly, this study aims to review the research on the application and impact of Scrum and Kanban, two prominent agile methodologies, in construction projects. By exploring existing research, the paper examines Scrum and Kanban's theoretical foundations and practical applications within this specific context. Furthermore, it investigates practical applications through case studies and relevant literature, analysing how Scrum and Kanban can be implemented in construction projects. The findings of this literature review can help project managers, Scrum and Kanban masters, and academics interested in construction project management and agile methodologies understand the use of Scrum and Kanban in managing projects in the construction industry.

Keywords: *agile methodologies, construction industry, kanban, literature review, project management, scrum.*

Introduction

The global construction industry is a behemoth, shaping skylines, carving infrastructure through challenging terrains, and fostering economic development. It encompasses many projects, from intricate historical restorations to colossal megastructures (Alzahrani & Emsley 2013). However, this dynamism brings with it many problems as well as its advantages. While it fosters innovation and pushes the boundaries of engineering, it also creates a complex and ever-evolving landscape for project management (Han, 2013). Project complexity is rising, driven by increasing technological integration, heightened environmental concerns, and growing client expectations for efficiency and sustainability (Conforto et al., 2014). Traditional project management methodologies, often characterized by rigid structures and linear workflows, may struggle to keep pace with this evolving landscape.

According to Nagel and Dove (1991), agile methodologies are seen as a game-changer in response to these challenges. Agile approaches offer a compelling alternative to traditional project management with their core principles of flexibility, collaboration, and continuous improvement. Conforto et al. (2014) emphasize iterative development cycles, allowing for rapid adaptation to changing project requirements or unforeseen circumstances. Additionally, the focus on collaboration fosters a more integrated project environment where diverse stakeholders can contribute their expertise and provide valuable feedback throughout the project lifecycle.

The concept of "agile management" gained prominence within project management by creating methodologies tailored for software development, like Scrum (Schwaber & Beedle, 2001). The individuals behind specific software development methodologies, often called "agile" or "lightweight methods," collaborated in drafting a document known as the Agile Manifesto. Since the Agile Manifesto was created, many research studies have examined the idea of "agility", and these approaches are now collectively known as Agile Project Management (APM). Amaral et al. (2011) characterize agile project management as a methodology rooted in a collection of principles aimed at streamlining the management process, enhancing flexibility and iteration to achieve improved performance metrics (such as cost, time, and quality), reducing managerial overhead, and fostering innovation and added value for clients.

This systematic literature review was conducted to understand the current status of using agile management methods such as Scrum and Kanban in construction project management. The resources collected through this study could lay the foundation for developing new management models for future construction projects by examining the benefits and challenges of applying these agile methods in construction projects.

For example, implementing Scrum and Kanban in construction projects can include increased transparency of project processes, collaboration, responsiveness, and efficiency. However, difficulties may also arise from applying these methods in the construction industry. These challenges include dealing with ever-changing requirements, the complexity of implementing agile methodologies in physical construction work, and the transformation of traditional construction culture.

The articles collected through this study can serve as an important resource for future research to create a hybrid management model that can be used in construction projects. A hybrid model can be designed to combine agile methods such as Scrum and Kanban while also considering the construction industry's specific needs.

Research Methodology

The study focused on using agile management methodologies, Scrum and Kanban, within the construction sector. A comprehensive meta-analysis was conducted, necessitating examining data obtained from various studies. A systematic literature review was performed to identify relevant studies, with Scopus chosen as the database for research. The keywords for the search were determined to be "construction industry", "construction projects", "construction sector", "Scrum", "Kanban", and "agile". Scopus' advanced search feature was used.

During the search, AND and OR boolean operators were used. The search consisted of two lines, with the first line containing "Scrum OR Kanban OR agile" and the second line containing "construction industry" OR "construction project" OR "construction sector." An AND boolean operator was used between the two lines. As a result of this search, 265 documents were obtained. To narrow down the scope and access relevant documents for the study, the filtering feature provided by the advanced search was also utilized. Subject area filters such as "limited to engineering", "limited to business and management and accounting", "limited to economics, econometrics, and finance", and "limited to multidisciplinary" were selected. Only the document type "limited to article" was chosen. The language was limited to English. There was no year limitation, but since the research study was conducted in the last quarter of 2023, articles added in 2024 were not included in this review study. After applying these filters, the number of documents was reduced to 85. Since the search terms are commonly used in many sectors, a screening was done to increase accuracy. During the screening process, non-English articles were eliminated, and the abstracts and titles of the articles were reviewed to exclude those that did not address the construction industry. Also, it was eliminated if the full paper could not be accessed. After this process, the number of documents was reduced to 29. For eligibility, the full texts of the 29 articles were examined to verify their relevance. Articles that did not address using Scrum and/or Kanban as management approaches in the construction industry were excluded. After this step, the number of articles was reduced to 15. These 15 articles, meeting the selection criteria defined for the research topic, create the final dataset. Figure 1 below shows the screening stages of documents and the amount of documents eliminated at the relevant stages.

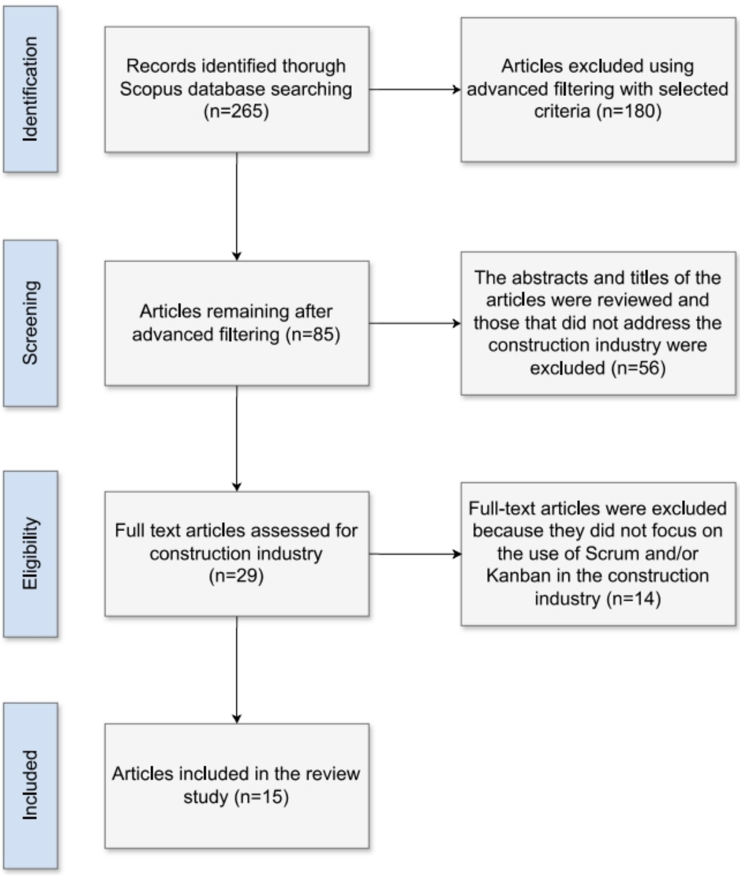

Figure 1: Flow diagram illustrating article selection and elimination.

Agile Management Methodologies in the Construction Industry: Scrum and Kanban

This part of the study examines the current research on using agile management methodologies, such as Scrum and Kanban, in the construction industry. A comprehensive search was done using well-known databases specializing in engineering and construction management literature. In order to access the trends and developments focusing on agile management practices in the construction industry, 85 different articles were examined from a total of 19 different databases. By looking at Table 1 below, the target audience can view the titles, author names, publication dates, and citation numbers of the 15 articles accessed as a result of the determined criteria. Highly cited articles can help researchers optimize the literature review process and identify the most important and influential sources.

Table 1. Analysis of publication citations.

Citation	Article	Author(s)	Publication Year
54	A lean-agile model of homebuilders' production systems	Weizhou Lu	2011
6	Agile project management for design-build construction projects: a case study	Saurabh S. Jethva	2022
5	Agile project management: Feasible methodology in construction industry	Aakanksha Ingle	2019
33	An empirical study of the impact of lean on the performance of the construction industry in UAE	Jaber Shurrab	2018
191	An innovative supply chain strategy for customized housing	Moh Naim	2003
42	Application of lean principles in the south african construction industry	I. Maradzano	2019
18	Developing a Risk Management Framework in Construction Project Based on Agile Management Approach	Mohammed Ahmed	2019
0	Estimation of speed in design teams: Implementation of agile tools for retail & construction management	Hugo Sanchez Vicente	2019
146	Exploring agile methods in construction small and medium enterprises: A case study	Francisco Loforte	2010
32	Framework for continuous agile technology roadmap updating	Rafael Carlos	2018
72	Implementing lean construction techniques and management methods in Chinese projects: A case study in Suzhou, China	Weiqi Xing	2021
15	Introducing agilean to construction project management	Selim Tugra Demir	2014
1	Providing a model to choose the most appropriate agile method in construction projects	Pouyandeh Faraz	2022
31	Sequential SWARA and fuzzy VIKOR methods in elimination of waste and creation of lean construction processes	Yücenur, G. Nilay	2021
22	Use of Scrum in the rehabilitation of a commercial building in Peru	Y Ormeño Zender	2021

Table 2 lists the articles according to keywords. Employing commonly used keywords in future studies to enhance data diversity and volume could be beneficial. The 15 related articles were examined, predominantly covering agile, project management, lean construction, waste elimination, and technology. Moreover, these articles also addressed subjects like small to medium-sized enterprises, supply chain, waste management, and decision-making. It was noted that these studies helped the construction industry complete complex projects per the intended success criteria. Agile management techniques are not commonly utilized in the construction industry, but they may be applied to nearly any large-scale project (Chia et al., 2022). Many articles state that applying these management forms, frequently used in the information technologies sector, will also benefit the construction industry. Examples include 'Prioritizing agile project management strategies as a change management tool in construction projects (Arefazar et al., 2019), Introducing agilean to construction project management (Demir & Bryde, 2014), Implementing lean construction techniques and management methods in Chinese projects: A case study in Suzhou, China (Xing et al., 2021), Examining the Agile Project Management Practices in the Malaysian Construction Industry (Chia et al., 2022), and A case Study on Agile And Lean Project Management In Construction Industry (Kashikar et al., 2016).

Table 2. Analysis of keywords in articles.

Article	Keywords
A lean-agile model of homebuilders' production systems	Agile, housing construction, lean, simulation
Agile project management for design-build construction projects: a case study	Agile, project management, case study
Agile project management: Feasible methodology in construction industry	Agile, technology, management, construction industry
Developing a Risk Management Framework in Construction Project Based on Agile Management Approach	Agile, Scrum, PMBOK, construction project, risk
Exploring agile methods in construction small and medium enterprises: A case study	Agile production, construction industry, small to medium-sized enterprises
Framework for continuous agile technology roadmap updating	Agile, innovation planning, project management
Implementing lean construction techniques and management methods in Chinese projects: A case study in Suzhou, China	Case study, Kanban system, last planner system, lean construction management
Introducing agilean to construction project management	Agile, agilean, lean, qualitative research
Providing a model to choose the most appropriate agile method in construction projects	Agile method construction management construction projects planning
Use of Scrum in the rehabilitation of a commercial building in Peru	Agile, construction management, Scrum, rehabilitation projects, construction

According to the data provided, the oldest publication related to the topic dates back to 2002, titled Enthusiasm, commitment and project alliancing: An Australian experience by Walker, while the newest publication is Agile Project Management for Design-Build Construction Projects: A case study by Jethva and Skibniewski, published in 2022. Figure 2 shows the number of articles published within the time span. 2019 and 2022 were the years with the most publications, with five publications each, ten in total. Looking at the last five years, it can be seen that there has been an increase in the number of publications on the subject. However, considering the last five years, it cannot be stated with certainty that there is a consistent yearly increase. Therefore, it is impossible to say with certainty that the topic has become more popular in the construction industry based on the facts provided. In addition, using the information which provided in Table 3, journals with more content on the subject can be examined in more detail in future studies.

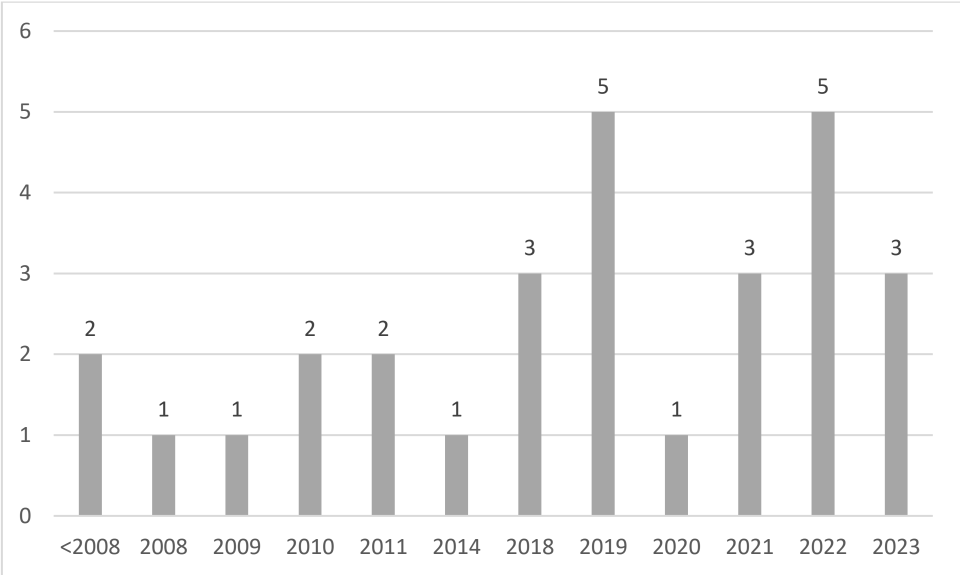

Figure 2: Distribution of the publications within the time span.

The examined articles, written by academics with diverse backgrounds and varying levels of analysis of the topic, demonstrate the diversity of interest in the subject. The articles were examined at three levels of analysis: global, national, and project scale. Nine articles were analysed at the global level, three at the national level, and another at the project scale. Examples of these articles include Agile project management: Feasible methodology in the construction industry (Ingle, 2019) as global, Application of lean principles in the South African construction industry (Maradzano et al., 2019) as national and Use of scrum in the rehabilitation of a commercial building in Peru (Ormeño Zender & García de Soto, 2020) as project.

Additionally, some articles address specific topics within particular countries. For instance, one article discusses the use of Scrum, an agile methodology for management, in restoring of a commercial building in Peru, titled Use of Scrum in rehabilitating of a commercial building in Peru (Ormeño Zender & García de Soto, 2020). Another article examines the applicability of lean management and construction approaches through a case study in Suzhou, China, titled Implementing lean construction techniques and management methods in Chinese projects: A case study in Suzhou, China (Xing et al., 2021). Yet another article focuses on a study conducted within the United Arab Emirates construction industry, titled. An empirical study of the impact of lean on the performance of the construction industry in UAE (Shurrab & Hussain, 2018). The fact that the subject is being addressed in significantly different countries indicates the global interest in the topic.

Conclusion

This paper has explored the existing literature on the use and potential effects of Scrum and Kanban, two prominent agile methodologies, in the context of construction industry. By examining theoretical foundations and practical applications as presented in various studies, the analysis aimed to determine the advantages and disadvantages of each methodology. The outcomes of projects in the construction industry may benefit from the application of both scrum and kanban, according to the findings of this literature review. Scrum's focus on iterative development and clear deliverables can benefit projects with well-defined goals. Conversely, Kanban's flexibility benefits projects with evolving requirements. However, the choice of methodology should be carefully considered based on specific project characteristics, stakeholder involvement, and other management needs.

While this review study provides insights, understanding its limitations is crucial. The review study is based solely on existing research identified for this study, and the data is confined within the limits set for this study. The methods used for identification, screening, and eligibility, including using only the Scopus database, restricting document types to articles only, including only English-language articles, and limitation to data up to the year of the study (2023), constrain this research. Future research endeavours could include and expand upon different databases and document types to explore practical challenges and advantages of implementing Scrum or Kanban methodologies. A study encompassing these extended boundaries could access more data.

Overall, this review study was carried out to comprehend the present situation of using agile management methods such as Scrum and Kanban in construction project management. Project managers, scrum and kanban masters, and academics interested in construction project management and agile methodologies, who are the target audience of this article, can learn the benefits and difficulties of applying these agile methods in construction projects by examining the documents used in this study. The documents gathered for this study can be a valuable source for future studies to develop a hybrid management model applicable to construction projects.

References

Ahmed, M. N., & Mohammed, S. R. (2019). Developing a risk management framework in construction project based on agile management approach. *Civil Engineering Journal*, *5*(3), 608.

Carlos, R., Amaral, D. C., & Caetano, M. (2018). Framework for continuous agile technology roadmap updating. *Innovation & Management Review*, *15*(3), 321-336.

Demir, S. T., Bryde, D. J., & Sertyesilisik, B., (2014). Introducing agilean to construction project management. *Journal of Modern Project Management*, *1*(3), 28-39.

Ingle, A. (2019). Agile project management: feasible methodology in construction industry. *International Journal of Engineering and Advanced Technology*, *9*(1), 5210-5213.

Jethva, S. S., & Skibniewski, M. J. (2022). Agile project management for design-build construction projects: a case study. *International Journal of Applied Science and Engineering*, *19*(1), 1-11.

Loforte Ribeiro, F., & Timóteo Fernandes, M. (2010). Exploring agile methods in construction small and medium enterprises: a case study. *Journal of Enterprise Information Management*, *23*(2), 161-180.

Lu, W., Olofsson, T., & Stehn, L. (2011). A lean agile model of homebuilders' production systems. *Construction Management and Economics*, *29*(1), 25-35.

Maradzano, I., Matope, S., & Dondofema, R. A. (2019). Application of lean principles in the South African construction industry. *South African Journal of Industrial Engineering*, *30*(3).

Naim, M., & Barlow, J. (2003). An innovative supply chain strategy for customized housing. *Construction Management and Economics*, *21*(6), 593-602.

Ormeño Zender, Y., & García de Soto, B. (2020). Use of scrum in the rehabilitation of a commercial building in Peru. *Construction Innovation*, *21*(2), 145-163.

Pouyandeh, F., Golabchi, M., & Taghizadeh, K. (2023). Providing a model to choose the most appropriate agile method in construction projects. *Proceedings of the Institution of Civil Engineers - Management, Procurement and Law*, *176*(1), 14-27.

Shurrab, J., & Hussain, M. (2018). An empirical study of the impact of lean on the performance of the construction industry in UAE. *Journal of Engineering, Design and Technology, 16*(5), 694-710.

Xing, W., Hao, J. L., Qian, L., Tam, V. W. Y., & Sikora, K. S. (2021a). Implementing lean construction techniques and management methods in Chinese projects: a case study in Suzhou, China. *Journal of Cleaner Production*, *286*, 124944.

Vicente, S. A., & Santos (2019). Estimation of speed in design teams: implementation of agile tools for retail & construction management. *Journal of Modern Project Management*, *6*(3), 142-155.

Yücenur, G. N., & Şenol, K. (2021). Sequential Swara and fuzzy Vikor methods in elimination of waste and creation of Lean Construction Processes. *Journal of Building Engineering*, *44*, 103196.

Factors Affecting Decision Making in Purchasing a House

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Abstract

The construction and real estate sector are among the sectors in which Turkey is most successful. The employment created by the sector and the potential to develop other sectors are very important. In this sector investors evaluate the factors that will serve the purpose of making a profit before starting a project. In projects with very high investment costs, such as construction, failure to realize the targeted sales rates within the targeted period will mean that not only the relevant business and its beneficiaries, but also other investors in the region and even the country's economy will be negatively affected. The goal of businesses is to make a profit and they need to understand potential customers. While analyzing the behavior of customers and examining the factors that affect their decision-making during real estate purchases are of great importance in maintaining the strength of the sector and making the right investments, it is undoubtedly the most important factor in deciding on an investment. The purpose of this study is to understand the customer dimension that construction sector investors should pay attention to when deciding on the implementation of their projects and to create a guide especially for small construction sector investors.

Keywords: *construction sector, decision making, real estate.*

Introduction

The main purpose of commercial enterprises is to make profits. In order to achieve this goal, the enterprises need to understand potential customer behaviors and act in accordance with these behaviors. The aim of this study is to reveal which factors people with potential to invest in housing pay attention to when making an investment decision. The sub-purpose of the study is to understand the customer dimension that companies implementing housing projects pay attention to - and should pay attention to - when making project decisions and to guide construction sector investors.

The answers to the questions of how the products of the construction industry, which is a locomotive sector and has a very important place in economic activities, are sold, and what factors customers take into consideration when making purchasing decisions, directly affects the decision-making situation of businesses that want to implement their projects.

As it is known, investments are economic actions that are intended to be made if a profit can be obtained in return. At this point, the most important investment decision in the construction sector is undoubtedly the factors that customers pay attention to when making a purchasing decision.

Within the scope of the study, it was aimed to understand what features real estate customers look at when deciding to purchase houses among real estate market. The reason for choosing this target was the problem of customers, and therefore construction companies, taking an unconscious approach when realizing a project or investing in an existing project (Binici et al., 2003).

The real estate sector is a locomotive sector with a very wide range. Almost every structure, starting from a piece of land to the largest factories, is a part of the real estate sector. The aim of all projects carried out in this sector, which has been developing rapidly in our country, especially in recent years, is to make a profit. While this profit can sometimes be financial gain, sometimes it is a social benefit. Undoubtedly, in every project that is started, preliminary calculations regarding these gains are made and the steps are taken by the developers accordingly.

In this study, the factors that should be taken into consideration when deciding on project investment in housing projects, which have an important place in the real estate sector, were examined by revealing the factors that affect house purchasing decision of individuals who has bought/potentially buy a house. The study covers new housing projects within the real estate sector.

Elements That Determine Real Estate Value

The elements that determine the real estate value are structuring and technical factors, geographical factors, government practices, legal factors, economic factors, social factors, and environmental factors (Amca, 2016).

There are internal factors that add value to a property or cause its value to decrease. It is possible to define internal elements as elements directly related to real estate. It is possible to summarize these as physical conditions, usefulness, famine, and transferability (Tatoğlu, 2008).

There are also external factors that are not directly connected to real estate, they are factors that closely concern and affect it. It is possible to summarize external elements as social factors and economic factors. The environment in which a real estate is located and the changes there directly affect its value. For example, variables such as population, migration to the environment, the status of education and other social facilities, the architectural design, landscape, and sociocultural structure of the region directly affect the balance of demand for real estate (Alp & Yılmaz, 2000).

The macroeconomic structure of the country and the financial situation of people are among the most important factors in deciding when people want to buy a real estate. Decreasing and increasing market returns, changes in employment, availability of money and credit, price levels in the market, interest rates, tax liabilities, wage levels and other factors that have direct or indirect effects on purchasing power, expectations and changes in markets and economic expectations, building, repairing and construction costs, under-construction and planned new developments around the real estate, suitable vacant and structured land stocks in the surrounding area, the economic base of the region and the subdivision are the economic factors that should be taken into consideration when determining the value of a real estate (Tatoğlu, 2008).

Factors Affecting Consumer's Purchasing Idea

The factors that affect consumer behavior are divided into separate headings as personal factors, social factors, economic factors, socioeconomic factors, psychological factors, cultural factors and economic factors.

Personal factors are age, gender, reading habits, consumer's region of residence, consumer's values and beliefs. Social factors are the individual's family, culture and subculture, status, and social class. Psychological factors are the consumer's perspective, the consumer's beliefs and religion, wishes, desires and needs (Sayılgan, 2010). Cultural factors are culture, subculture, social class (Satıcı, 1998). Socio-Cultural factors are urbanization rate, religion, history and language (Uçal, 2013).

It is a known fact that economic factors affect individuals' purchasing behavior. The income levels of the customer base that businesses address is an extremely important factor for businesses. Because businesses develop different strategies for the masses with low economic levels and those with high economic levels, and thus can be effective in both areas. In addition, determining the rate of discounts to be made, acting in accordance with the purchasing power of individuals and ultimately influencing the behavior of consumers are shaped in this direction, and the business can increase its profit level with these approaches. To put it in more concrete terms; keeping the price of the service or goods to be sold high in the segment with low-income level will cause the consumers of that segment to move away and a decrease in sales volumes will occur. Or, selling a product or service of such poor quality that it does not deserve the price in a segment with a high-income level will also affect the behavior of consumers in that segment. Consumer behavior in a market area where there are businesses that take economic factors into consideration is quite different from the behavior towards businesses that do not take these factors into consideration (Sayılgan, 2010).

Other factors mentioned above affect the purchasing behavior of individuals also. For example, the purchasing behavior of an individual growing up in a crowded family and an individual growing up in a nuclear family may be quite different from each other. Differences such as age, status, social class, culture, reading habits, cultural differences, religious beliefs, psychological state, urbanization rate and economic factors affect the purchasing behavior of individuals (Sayılgan, 2010; Satıcı, 1998; Uçal, 2013).

Material and Methods

The aim of this study is to reveal which factors and to what extent people who are considered to have a high potential to purchase a house pay attention to when making investment decisions. The sub-purpose of the study is to enable companies carrying out housing projects to understand better the customer dimension that they pay attention to - and should pay attention to - when making investment decisions, and to guide especially construction sector investors.

In line with the above-mentioned purposes, a cross-sectional survey study was conducted with people who have purchased real estate before or were considered to have a high potential to do so. This survey study attempted to provide a general picture of the conditions under which people are willing to pay for a very costly product such as real estate. The information obtained will provide insight into what features the relevant real estate project should have in order to achieve the desired sales targets in a real estate project at the planned time. In this way, it will be possible for real estate projects to become more successful and have a higher profitability rate.

In the survey, participants were asked 17 questions, and the answers were received in accordance with the Likert Scale. The participants were asked questions about places and proximity, the characteristics of the house itself and the economic situation of the country. They were asked to answer the questions by choosing among the following answers: 1-strongly disagree, 2-partially disagree, 3-undecided, 4-partially agree, 5-strongly agree. Participants were offered multiple response options for some questions.

Survey data were analyzed digitally using the SPSS 21.0 for Windows computer program. Chi-square test was used to evaluate the relationships between categorical variables (gender, education and answers to questions). In the test, Pearson asymptotic 2-way significance values $p<0.05$ were considered significant.

Results

The survey was conducted in 2019 with 136 people who were considered to have high potential to purchase housing (Bahat, 2019). During the survey process, answers to the survey questions were received from 90 people face to face and 46 people via e-mail. Approximately, 40% of the participants participated in the survey from Erzurum, 40% from Istanbul, 10% from Giresun and 10% from Trabzon.

Of the 136 people participating in the study, 67 were male and 69 were female participants, male participants constitute 49% of the total participants and female participants constitute 51%.

The average age of male participants was 39±11, the average age of female participants was 35±10, and the total average age of participants was 37±11.

The age range of male participants was 23-62, the age range of female participants was 23-77, and the age range of total participants was 23-77.

Results Evaluated in the Context of Places and Proximity

“When buying a house, which of the following options are important for you to be close to?” When the answers to the question were considered, the most important thing is the proximity of the house to the workplace (4.64 ± 0.68). This is followed by proximity to public transportation (4.53±0.84), green areas (4.44±0.92), hospital (4.28±0.99), main road (4.06±1.13), mosque (4.05±1.17) and finally the shopping center (3.86±1.00).

When the answers to the question "How close should the proximity be to these places?" were considered, the most preferred type of proximity was walking distance (4.39±1.25). This was followed by single vehicle (3.33±1.69), double vehicle (1.32±0.79) and finally more than two vehicle (1.14±0.63) proximity types.

The average of the answers given to the questions regarding other features in house purchasing are summarized according to the degree of importance given in Table 1.

Table 1. The importance given to other features in house purchasing.

Questions	Averages
When buying a house, do you pay attention to its infrastructure (parking lot, heating, elevator, fire escape, etc.)?	4.81 ± 0.48
Are direction and sun important to you when buying a house?	4.73 ± 0.60
When buying a house, do you pay attention to what its value will be if you sell it in the future?	4.68 ± 0.67
Do you pay attention to noise when buying a house?	4.68 ± 0.67
Do you pay attention to the type of heating (central, independent) when buying a house?	4.64 ± 0.70
Is it important for you that the construction company is a well-known/reliable company when purchasing a completely finished house?	4.59 ± 0.76
When buying a house, do you pay attention to the physical conditions of the land (slope, soil structure, topographic features)?	4.40 ± 0.80
Do you pay attention to the depreciation period (purchase value / monthly rent) when buying a house?	4.40 ± 0.87
Is the economic situation of the country a criterion for you when purchasing a house?	4.33 ± 0.98
When buying a house, do you pay attention to whether the materials used in it belong to known brands?	4.30 ± 0.93
When buying a house, do you pay attention to whether it is within the site?	4.23 ± 0.92
Is the number of floors/height of the building important to you when buying a house?	4.22 ± 1.04
Do you pay attention to the operating/usage costs when purchasing a house?	4.21 ± 0.89
When buying a house, do you pay attention to its sustainability?	4.21 ± 0.92
When buying a house, do you pay attention to the distribution of independent sections in the building (how many 1+1, 2+1, 3+1, etc.)?	4.10 ± 1.18

As can be seen from the information presented in Table 1, the most important feature was the infrastructure features of the house, such as "parking lot, heating, elevator, fire escape, etc." (4.81 ± 0.48). The least important feature was the distribution of independent sections in the building (4.10 ± 1.18) (Bahat, 2019).

Factors Associated with Responses by Gender

According to the gender of the participants included in the survey no significant difference was detected between the importance they gave to proximity to hospital (p=0.779), to shopping mall (p=0.66), to main road (p=0.198), to workplace (p=0.397), to green areas (p=0.339), to mosque (p=0.853), and to public transportation (p=0.109).

When the gender of the participants in the study and their transportation preferences to places were evaluated, it was found that the importance given to "walking distance" preference by the male gender was almost significantly higher than the female gender (p = 0.06).

No significant difference was detected between the gender of the participants in the study and their transportation preferences for single vehicle (p=0.121), double vehicle (0.405) and more than two vehicles (0.855).

A highly significant difference was detected between the gender of the 134 participants included in the study (2 participants did not share information on the relevant subject) and their attention to operating/usage costs (p = 0.014). The rate of female gender paying attention to operating/usage costs is significantly higher than male gender.

According to the gender of the participants included in the survey no significant difference was detected between the importance they gave to the economic situation of the country (p = 0.549), to the value in case of future sale (p = 0.167), to the physical conditions of the land (p = 0.992), to the infrastructure of the house (p = 0.663), to the depreciation period (p = 0.203), to within the site or not (p=0.200), to noise (p=0.232), to direction and sun conditions (p=0.124), to sustainability (p=0.671), to number of floors and height of the building (p=0.286), to heating type (p =0.785), to independent section distribution (p=0.744), to brands of the materials used (p=0.100), and to be constructed by a reliable company (p=0.992). (Bahat, 2019).

Factors Associated with Responses by Education

A significant difference was detected between the educational status of the 110 participants included in the study (26 participants did not share information on the relevant subject) and the importance they gave to the proximity of the house to the shopping center (p = 0.03). As the level of education increases, the importance given to proximity to the shopping center also increases significantly.

A highly significant difference was detected between the educational status of the 111 participants included in the study (25 participants did not share information on the relevant subject) and the importance they gave to the proximity of the house to the mosque (p = 0.007). As the level of education increases, the importance given to proximity to the mosque decreases significantly.

According to the gender of the participants included in the survey no significant difference was detected between the importance they gave to proximity to hospital (p=0.200), to main road (p=0.678), to workplace (p=0.245), to green areas (p=0.756), and to public transportation (p=0.987).

When the education levels of the participants in the study and their transportation preferences to places were evaluated, there was no significant difference between walking distance ($p = 0.647$), single vehicle ($p = 0.183$), double vehicle ($p = 0.988$) and more than two vehicles ($p = 0.992$).

According to the educational level of the participants included in the survey no significant difference was detected between the importance they gave to economic situation ($p=0.195$), to value in case of sale ($p=0.827$), to physical conditions of the land ($p = 0.465$), to infrastructure of the house ($p = 0.693$), to amortization period ($p=0.867$), to operating/usage cost ($p=0.640$), to being within the site ($p=0.797$), to noise ($p=0.902$), to direction and sun conditions ($p=0.979$), to sustainability ($p=0.815$), to number of floors and height of the building ($p=0.475$), to type of heating ($p=0.773$), to distribution of independent sections ($p=0.159$), to brands of materials used ($p=0.246$), and to construction by a reliable company ($p=0.323$). (Bahat, 2019).

Discussion

The most important feature given by potential investors was the features of the house's infrastructure such as elevator, parking lot and fire escape (average importance is 4.81). For this reason, housing developer companies should prioritize and enrich these features of the house's infrastructure as much as possible, which will play an important role in turning their investments into profit.

Direction and sun, future value of the house and noise were among the top four most important features. The importance given to direction and sun shows that great importance should be given to the direction of houses. The fact that south-facing houses are highly preferred in cold places also points to this. It is important for investor companies to pay maximum attention to the direction and sun conditions when determining the prices of houses. It must be in the interests of companies to work to ensure maximum benefit from daylight and to position buildings so as not to block each other's rays.

As expected, the survey’s result showed that the high cost of housing investment increased the importance given to the future value of the house. The fact that the participants attach serious importance to the depreciation period reveals that investor companies should attach importance to the rent multiplier value (value of the house / rent amount). It is very important for housing developer companies to consider the relationship between housing prices and rental amounts around the land they intend to invest in, and also to take into consideration real estate projects under development, which will significantly affect this amount, and areas in the surrounding area suitable for real estate development, in their investment decisions.

It was seen that the participants also attach great importance to the noise in the environment (average importance 4.65). Considering that there will be living in the house to be purchased, the given importance to noise appears to be a perfectly normal choice. In the survey it was found that closeness to the workplace and public transportation is given great importance and the first choice for this proximity is walking distance. It is a predicted reality that noise will increase in places close to workplaces and public transportation. For this reason, developer companies should consider taking precautions against the noise around the residence from entering the land where housing is developed. The use of sound-deadening barriers and paying attention to sound insulation on the exterior and interior walls of the residence are features that investor companies should take into consideration.

According to results of the survey, it was also important to consider whether the heating type is central or independent. It is a known fact that individuals who spend time at home generally attach importance to the central heating system, while individuals who spend a significant part of their time outside prefer the independent heating type. In any case, choosing the heating type in line with the preferences of potential customers will benefit developers. While the central system comes to the fore in places where elderly individuals spend a lot of time at home, independent heating type should be brought to the fore in places where individuals who work hard and live alone.

According to the results of the survey, when purchasing a house, the fact that the house was built by a known/reliable company ranked 6th, while the brands used in the house belonging to well-known companies could only find a place in the 10th place. This result shows how important the trust feature is in real estate development. People attach importance to the fact that the housing developer is a well-known/reliable company rather than the materials used in their investments belonging to known brands.

According to the results; type of proximity most preferred by the participants was walking distance proximity. This was followed by single vehicle, double vehicle and finally more than two vehicle proximity types. In the study of Straszheim (1973), it was revealed that the accessibility of the location of the residence and its proximity to the workplace are important factors in the choice of residential location and the amount of housing purchased (Daşkıran, 2015). In his study for Izmir province, Üçdoğruk (2016) also found a significant relationship between the location of the houses and their prices. As can be seen from the answers given to the closeness questions in the survey, the results of the survey conducted by Straszheim (1973), Üçdoğruk (2016) and the survey are in the same direction; potential customers attach great importance to the location of the house when purchasing a house.

When the gender of the participants in the study and their transportation preferences to places were evaluated, the importance given to "walking distance" preference by the male gender was almost significantly higher than the female gender ($p = 0.06$). This excess can be interpreted as the higher working rate of male individuals and therefore they attach more importance to proximity to the workplace.

According to the survey, females pay significantly ($p= 0.014$) more attention to operating/usage costs than males. This could be because of females are more present in-home life than males; as a result, they pay more attention to household costs.

As the level of education go higher, the importance given to proximity to the shopping center also increases significantly. This increase could be interpreted as an increase in the level of income as the level of education increases, and individuals with higher incomes are more likely to go to shopping malls.

The most striking and significant difference in the study ($p = 0.007$) was found between the level of education and the importance given to proximity to the mosque. As the education level of individuals increases, the importance they attach to proximity to the mosque decreases significantly. The reason for this can be considered as incorrect religious education or the fact that the wrong practices of people who appear to be religious are more noticed by the educated segment, and as a result, the educated segment moves away from religion.

As a result, it should be stated that it will be in the interest of investor companies to understand the customer dimension of the business, to attach the necessary importance to studies such as the surveys conducted in this study, and to develop their real estate projects in line with the information they obtain from the studies.

References

Alp, A., & Yılmaz, M. (2000). *Gayrimenkul finansmanı ve değerlemesi*. Istanbul Stock Exchange Publications.

Amca, F. (2016). *Gayrimenkul değerlemesi ve Denizli Merkez'de bir uygulama* [Master thesis]. Pamukkale University.

Bahat, M. (2019). *Konut satın alımında karar vermeyi etkileyen faktörler* [Master thesis]. Mimar Sinan Fine Arts University.

Binici, H., Temiz, H., Arı, N., & Kuşat Gürün, D. (n.d.). *Osmaniye'de kentleşme*. http://www.imo.org.tr/resimler/ekutuphane/pdf/11174.pdf

Satıcı, Ö. (1998). *Tüketici davranışları ve alıcı davranışları tüketici satın alma davranışlarını etkileyen faktörler* [Master thesis]. Ankara University.

Sayılgan, E. (2010). *Medya işletmelerinde pazarlama yönetimi* (1st ed.). Beta Publications.

Straszheim, M. (1973). Estimation of the demand for urban housing services from household interview data. *Economics and Statistics*, *55*, 1.

Tatoğlu, H. (2008). *Gayrimenkul değerlemesi ve Eryaman/Ankara bölgesinde bir uygulama* [PhD thesis]. Gazi University.

Uçal, H. (2013). *Sosyo-kültürel ve politik faktörlerin seçilmiş makroekonomik değişkenler üzerine etkisi* [Master thesis]. Adnan Menderes University.

Üçdoğruk, Ş. (2016). İzmir ilinde emlak fiyatlarına etki eden faktörler - hedonik yaklaşım. *Dokuz Eylül University Faculty of Economics and Administrative Sciences Journal*, *16*(2).

A Survey of Barriers and Enablers of the Successful Transition of Military Veterans into the Construction Industry

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Abstract

This paper investigates strengths and weaknesses of military veterans transitioning into civilian employment, with a focus on careers in the architecture, engineering, and construction (AEC) sectors. As the aging AEC workforce confronts challenges in attracting skilled workers, veterans present a valuable yet underutilized talent pool. Following focus group discussions with human resources professionals that identified key areas of strength, e.g., teamwork and leadership, as well as weaknesses, e.g., difficulty veterans face in translating their military skills to civilian applications and managing interview-related stress, a survey completed by a pool of veterans provided insights from the candidates' perspectives. The research contributes new insights into the unique challenges and opportunities veterans encounter in civilian job interviews, particularly within the AEC domain. Findings will guide the development of actionable strategies to enhance veterans' interview performance and inform interventions designed to integrate veterans into the civilian labor market, thus enriching the workforce with their distinct skills and experiences.

Keywords: *construction workforce, correlation analysis, interview performance, veterans.*

Introduction

The architecture, engineering, and construction (AEC) workforce is aging and facing major hurdles in hiring and retaining motivated and skilled workers (Brown et al., 2020; Chan et al., 2020; Sakib, 2022; Sokas et al., 2019). While the supply of new labor is limited, attracting, reskilling, and retaining of career change workers from other sectors of the economy to the AEC domain pose unique challenges. Military veterans are one of those non-traditional workforce groups that are attractive to the AEC industry. Construction jobs have been, in fact, a popular career choice among veterans (Azhar et al., 2016; Behzadan & Chaspari, 2021), given the skills they possess, including motivation, leadership, and discipline. However, veterans comprise only about 6.5% of the U.S. construction workforce, which is 10% lower than 2019 (Logan, 2023; United States Bureau of Labor Statistics, 2020; United States Census Bureau, 2020; United States Department of Labor, 2022; Vespa, 2020). Every year, considerable resources are devoted to developing service personnel's teamwork, stress management, and leadership skills (National Veterans' Training Institute, 2014). However, over two-thirds of job-seeking veterans report that the highest obstacle in their transition process is finding a career in the civilian sector (Prudential Financial Inc., 2012). Challenges, such as difficulty translating military-specific skills to the civilian setting and negative stereotypes held by some civilians toward veterans, have been cited as barriers to veterans seeking civilian jobs (Harrell & Berglass, 2012; Keeling et al., 2018; Shields et al., 2016; Stone & Stone, 2015). One major hurdle faced by many veterans seeking careers in the civilian sector (e.g., AEC industry) is the employment interview, which is used to assess a job candidate's knowledge, skills, or other traits determined to be predictive of successful job performance (Huffcutt & Arthur, 1994; Levashina et al., 2014). For many veterans, the employment interview is the first step of assimilation into the civilian workplace, which can turn the interview experience into an episode of nervousness or anxiety. In many cases, especially for managerial positions, a successful job interview stands between a veteran job seeker and a career in the construction or engineering sector (Smith et al., 2015). In a 2012 survey by Prudential, 85% of the 2,456 veteran respondents stated that they needed help to "close" a job interview (Prudential Financial Inc., 2012). Since employment interviews are often assigned significant weight in the hiring decision, they can disadvantage veterans if they do not perform as well as their civilian counterparts. This may compromise the interviewee's performance and potentially impede their successful career transition (Behzadan & Chaspari, 2021; Smith et al., 2021).

Methodology

A 10-item survey was administered to military veterans to obtain insights into their interview strengths and weaknesses in the civilian job interview. This survey was guided by findings from a focus group where 14 (8 veterans, 6 non-veterans) human resources professionals (7 from AEC firms) with experience in interviewing veterans shared their observations from interviewing veterans. The emerging themes from the focus group discussions included key areas of strength, e.g., teamwork and leadership, as well as weaknesses, e.g., difficulty in translating military skills to civilian applications and managing interview-related stress (Hagen et al., 2022). Further analysis on how strengths and weaknesses reported in the survey correlate with various demographic and personality factors, such as years of service, rank, participation in employment transition programs, employment status, emotional stability, and agreeableness, was conducted. The inclusion of emotional stability and agreeableness was in part driven by their relevance to identified themes of nervousness and interpersonal skills, respectively.

Participants and Data Collection

Data was collected online via Qualtrics over a span of 20 months, commencing in August 2021. Recruitment was done by distributing a study flyer and signup link on social media (e.g., Facebook, LinkedIn, Instagram), the American Psychological Association's Division 9 (Military Psychology) listserv, personal contacts in the U.S. Department of Defense-affiliated organizations (such as research labs and consulting firms) with instructions for broad distribution, Texas Veterans Commission, and the U.S. Department of Veterans Affairs. The study flyer was also sent via Texas A&M University's bulk email system, reaching out to a relatively large veteran community on campus. Collectively, from 396 respondents who expressed interest, 356 were qualified to participate (i.e., self-identified U.S. veterans, aged 18 or older, who were proficient in English) and received the survey link. Biweekly follow-up emails were sent until the survey closed on April 2023. Participants consented before taking part in the survey. Out of 356 individuals who received the link, 122 completed the survey. However, 29 were excluded due to incomplete data or inconsistency in verifying their veteran status. This verification involved a captcha and four repeating veteran-specific questions in the survey to confirm human and veteran status, with mismatches leading to exclusion from the final sample. The final study sample included 93 veterans, mostly male (70%) and White (62%), with ages ranging from 22 to 80 years (Mean = 40.4; SD = 11.82). On average, participants had exited military service 7.15 years before the study (Mean = 3.00; SD = 10.56).

Survey Details

Respondents filled out a survey of their perceived strengths and weaknesses in civilian job interviews, demographic information, and levels of emotional stability and agreeableness. Collected data were analyzed in relation to the perceived interview strengths and weaknesses to provide deeper insights into these areas.

Strengths and Weaknesses

The survey included a set of 10 items created based on the themes that emerged from previously conducted focus group discussions with human resource professionals (Hagen et al., 2022). Each theme was assessed by 1-3 survey items. Respondent rated how each item described their experience in civilian job interviews using a 5-point Likert scale (1: strongly disagree; 5: strongly agree). To limit survey fatigue (incomplete responses), the measure was intentionally kept brief (Liu & Wronski, 2018).

Demographics

Respondents provided data on their age, gender, educational background, length of military service, and military rank. They also indicated their current employment status, whether they were deployed while serving, if they were affiliated with any veteran organization, and if they had taken part in any program designed to help them transition to the civilian life.

Emotional Stability and Agreeableness

Emotional stability and agreeableness were inferred from selected items in the Symptom Checklist 90-R (Derogatis, 1992). Participants evaluated the extent various issues had bothered them in the past week on a 5-point Likert scale (1: not at all; 5: extremely). For assessing emotional stability, 6 items were reverse-coded and chosen, while 2 items were identified as measures of agreeableness due to their close resemblance to the traits outlined in IPIP-NEO-300 (Goldberg, 1999). The internal consistency for emotional stability and agreeableness was found to be 0.77 and 0.88, respectively.

Table 1. Items and corresponding themes.

Theme	Item
1. Communicating soft skills	1. I am able to effectively convey my teamwork experience. 2. I am able to effectively convey my leadership experience. 3. I am able to effectively convey my experience in conflict resolution.
2. Confidence/Overconfidence	4. I feel confident. 5. I try not to come across as being arrogant.
3. Professionalism/Inauthenticity	6. I am professional
4. Ineffective translation of relevant technical skills acquired in the military and overexplaining	7. I find it difficult to explain how my military experience can be applied to civilian jobs. 8. I am able to effectively promote my skills (R).
5. Use of military jargon	9. I find it difficult to limit the excessive use of military jargon/acronyms.
6. Nervousness	10. I feel stressed.

Results

Table 2 reveals a range of Pearson's product moment correlation coefficient (PPMCC) between various themes from negligible (0.00) to moderate (0.54). Positive correlations within strength themes (r = 0.24 to 0.32) suggest that veterans with one strength typically exhibit others, with a similar trend observed among weaknesses (r = 0.32 to 0.35). The relationship between strengths and weaknesses varied widely, with the most significant negative correlation (r = -0.45 to -0.21) seen in veterans' difficulty in explaining their military experience (i.e., technical skills, overexplaining), suggesting this may impact strength themes the most. Other correlations between strengths and weaknesses were not statistically meaningful.

Table 2. Theme descriptive statistics and intercorrelations (*p <0.05, two-tailed).

Theme	*N*	*M*	*SD*	1	2	3	4	5
1. Communicating soft skills	93	3.90	0.68					
2. Confidence	93	4.04	0.78	0.54*				
3. Professionalism	93	4.34	0.80	0.24*	0.32*			
4. Technical skills and overexplaining	93	2.71	0.85	-0.45*	-0.38*	-0.21*		
5. Use of military jargon	90	2.87	1.27	0.13	-0.01	0.00	0.31*	

6. Nervousness	92	3.42	1.15	0.05	-0.03	0.03	0.35*	0.32*

As listed in Table 3, the validity of the six themes was evaluated by analyzing how they correlated and formed significant connections with various demographic (i.e., years of service, rank, participation in transition programs, employment status) and personality factors (i.e., emotional stability, agreeableness). While gender had no significant correlation with any of the themes, age exhibited a positive correlation with confidence ($r = 0.23$). Additionally, higher education level was linked to less difficulty in articulating technical skills from military experience ($r = -0.25$). Veterans with a longer service duration and higher rank faced more challenges in minimizing the use of excessive military jargon ($r = 0.25$; $r = 0.24$). Those who were employed exhibited greater confidence ($r = 0.28$) and were more adept at communicating their soft skills ($r = 0.25$). Moreover, those with deployment experience reported feeling less nervous ($r = -0.45$) during interviews. Also, while participation in veteran organizations did not show a significant connection to any of the identified themes, veterans who engaged in transition programs tended to report greater difficulties in curbing their use of military jargon, with a notable correlation ($r = 0.27$). Considering personality, those exhibiting higher levels of emotional stability and agreeableness also demonstrated stronger strengths across all themes and fewer weaknesses, particularly in effectively conveying their military experience.

Table 3. Descriptive statistics and correlations between themes and other variables (*p <0.05, two-tailed).

Other vars.	***N***	***M***	***SD***	**COM**	**CONF**	**PROF**	**TECH**	**JARG**	**NERV**
Age	92	40.40	11.82	0.17	0.23*	0.14	-0.20	-0.02	-0.05
Sex[a]	92	-	-	0.12	0.11	-0.04	-0.06	-0.03	0.11
Education	92	6.00	1.30	0.09	0.11	0.07	-0.25*	-0.05	-0.10
Employment[b]	90	-	-	0.25*	0.28*	0.16	-0.10	0.01	0.07
Deployment[c]	69	-	-	-0.15	-0.22	0.04	0.06	-0.16	-0.26*
Years of Service	71	12.89	9.00	0.09	0.16	0.03	0.03	0.25*	0.15
Rank[g]	89	1.82	0.90	0.16	0.10	-0.15	-0.08	0.24*	-0.01
Membership in Veteran Organization[e]	71	-	-	0.04	-0.01	0.12	-0.16	0.21	-0.05
Participation in Veteran Transition Programs[f]	70	-	-	0.11	0.17	0.12	-0.16	0.27*	0.10
Emotional Stability	88	4.80	0.99	0.27*	0.43*	0.23*	-0.24*	0.05	-0.08
Agreeableness	84	5.50	1.10	0.25*	0.35*	0.31*	-0.23*	-0.02	-0.04

Note. COM = Communicating soft skills, CONF = Confidence, PROF = Professionalism, TECH = Technical skills and overexplaining, JARG = Use of military jargon, NERV = Nervousness. [a]0 = Male *and 1 = Female.* [b]*0 = Unemployed and 1 = Employed.* [c]*0 = had not been deployed and 1= had been deployed.* [d]*1 = E, 2 = W, and 3 = O;* [e]*0 = Not a member and 1= a member.* [f]*0 = did not participate and 1= participated.* [g]*Rank as operationalized in the raw data displays a similar pattern of results.*

Discussion

The association of personality traits with stronger interview strengths and fewer weaknesses supports the notion that these aspects are significant predictors of interview success, offering a meaningful interpretation of the outcomes of this research. While civilian interviews may seem unfamiliar, many veterans have relevant experience from military board interviews and should use key skills valued in civilian contexts (e.g., adaptability, project management, teamwork, leadership). It is also vital to address potential weaknesses (e.g., use of military jargon) by practicing the translation of military experiences into civilian-appropriate language. Moreover, engaging in mock interviews and seeking interview coaching could provide crucial practice and feedback, improving veterans' interview performance (Maurer & Solamon, 2006; Maurer et al., 2001; Perkins et al., 2022; Tross & Maurer, 2008). For hiring AEC firms, it is recommended to utilize structured interviews, as well as train interviewers to evaluate veteran candidates more objectively and understand the unique challenges they may face during interviews. This dual strategy benefits both veterans in highlighting their skills and hiring firms in recognizing the contributions veterans bring to the construction workforce.

Conclusion and Limitation

This research was motivated by the challenges faced by military veterans during civilian job interviews. Findings explain the critical nature of employment interviews as gateways for veterans seeking to join the civilian workforce, particularly in AEC fields. While the research highlights veterans' teamwork and leadership skills, it also cites key challenges, such as the difficulty in translating military skills to civilian job requirements and managing interview-related anxiety, which is especially pertinent to careers in the AEC domain. Through empirical testing and validation, a framework was established for identifying strengths and weaknesses that could influence the interview outcome for veterans. Interventions, such as interview coaching and the use of mock interviews, might improve veterans' skills, boost confidence, and enhance their ability to articulate their qualifications in terms relevant to the hiring AEC firms. While it is essential to acknowledge the limitations due to the sample size and sampling methods, which may affect the generalizability of the results, the outcomes of this work provide a foundation for future studies involving a larger, more diverse participant pool and utilizing multi-source data collection strategies. Findings can also lead to the development of tailored training programs that specifically address veterans' needs, thereby facilitating their successful transition into the civilian workforce and enriching the AEC firms that hire them. Lastly, this research may serve as a call to action for policymakers and AEC business leaders to create supportive environments that recognize and leverage veterans' unique skills and experiences, and acknowledge and fully utilize their contributions in civilian roles. Ultimately, this can lead to increased chances of employment, customized training and professional development programs that address the specific needs of the AEC industry, and more inclusive workplaces where all employees are offered adequate skills and opportunities to achieve long-term success.

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References

Azhar, S., Noel, W., Nadeem, A., & Akhanova, G. (2016). Veteran workforce development: how veterans can make a positive impact on workforce development in the construction industry. *Proceedings of CIB World Building Congress*, Finland.

Behzadan, A. H., & Chaspari, T. (2021). *Panel report on veteran, race, and gender bias in tech hiring*. Texas Data Repository. https://doi.org/10.18738/T8/SLYTC9

Brown, S., Brooks, R. D., & Dong, X. S. (2020). *Coronavirus and health disparities in construction*. https://stacks.cdc.gov/view/cdc/90044

Chan, A. P. C., Chiang, Y.-H., Wong, F. K.-W., Liang, S., & Abidoye, F. A. (2020). Work–life balance for construction manual workers. *Journal of Construction Engineering and Management*, *146*(5), 04020031.

Derogatis, L. R. (1992). *SCL 90 R administration, scoring and procedures manual II for the revised version and other instruments of the psychopathology rating scale series*. Clinical Psychometric Research.

Goldberg, L. R. (1999). A broad-bandwidth, public domain, personality inventory measuring the lower-level facets of several five-factor models. *Personality psychology in Europe*, Netherlands.

Hagen, E., Sakib, M. N., Rani, N., Nirjhar, E. H., Nenkova, A. N., Chaspari, T., Chu, S. L., Behzadan, A. H., & Arthur, Jr., W. (2022). *Interviewer perceptions of veterans in civilian employment interviews and suggested interventions*. *Proceedings of IMTA Conference/International Applied Psychology Symposium*, Raleigh.

Harrell, M. C., & Berglass, N. (2012). *Employing America's veterans*. Center for a New American Security. https://www.cnas.org/publications/reports/employing-americas-veterans-perspectives-from-businesses

Huffcutt, A. I., & Arthur, W. (1994). Hunter and Hunter (1984) revisited: interview validity for entry-level jobs. *Journal of Applied Psychology*, *79*, 184-190.

Keeling, M., Kintzle, S., & Castro, C. A. (2018). Exploring U.S. veterans' post-service employment experiences. *Military Psychology*, *30*(1), 63-69.

Levashina, J., Hartwell, C. J., Morgeson, F. P., & Campion, M. A. (2014). The structured employment interview: narrative and quantitative review of the research literature. *Personnel Psychology*, *67*(1), 241-293.

Liu, M., & Wronski, L. (2018). Examining completion rates in web surveys via over 25,000 real world surveys. *Social Science Computer Review*, *36*(1), 116-124.

Logan, D. (2023). *Veteran employment in construction increases in 2022*. https://eyeonhousing.org/2023/04/veteran-employment-in-construction-increases-in-2022/

Matthew, S., Smith, J. D., Jordan, N., Sherwood, K., McRobert, E., Ross, B., Oulvey, E. A., & Atkins, M. S. (2021). Virtual reality job interview training in transition services: results of a single-arm, noncontrolled effectiveness-implementation hybrid trial. *Journal of Special Education Technology*, *36*(1), 3-17.

Maurer, T. J., & Solamon, J. M. (2006). The science and practice of a structured employment interview coaching program. *Personnel Psychology*, *59*(2), 433-456.

Maurer, T. J., Solamon, J. M., Andrews, K. D., & Troxtel, D. D. (2001). Interviewee coaching, preparation strategies, and response strategies in relation to performance in situational employment interviews: an extension of Maurer, Solamon, and Troxtel (1998). *Journal of Applied Psychology*, *8659*(4), 709-717.

National Veterans' Training Institute (2014). *21 strengths arising from military experience*. https://ucnet.universityofcalifornia.edu/working-at-uc/your-career/veterans/_files/21_Strengths_Arising_From_Military_Experience.pdf

Perkins, D. F., Davenport, K. E., Morgan, N. R., Aronson, K. R., Bleser, J. A., McCarthy, K. J., Vogt, D., Finley, E. P., Copeland, L. A., & Gilman, C. L. (2022). The influence of employment program components upon job attainment during a time of identity and career transition. *International Journal for Educational and Vocational Guidance*, *23*, 695-717.

Prudential Financial Inc. (2012). *Veterans' employment challenges: perceptions and experiences of transitioning from military to civilian life*. http://hdl.voced.edu.au/10707/291614

Sakib, M. N. (2022). The future workforce: exploring the role of artificial intelligence and technology in workforce skilling [PhD thesis]. Texas A&M University.

Shields, D. M., Kuhl, D., Lutz, K., Frender, J., Baumann, N., & Lopresti, P. (2016). *Mental health and well-being of military veterans during military to civilian transition: review and analysis of the recent literature*. Report prepared for Veterans Affairs Canada and the Canadian Institute for Military and Veteran Health Research, Vancouver.

Smith, M. J., Boteler Humm, L., Fleming, M. F., Jordan, N., Wright, M. A., Ginger, E. J., Wright, K., Olsen, D., & Bell, M. D. (2015). Virtual reality job interview training for veterans with posttraumatic stress disorder. *Journal of Vocational Rehabilitation*, 42, 271-279.

Sokas, R. K., Dong, X. S., & Cain, C. T. (2019). Building a sustainable construction workforce. *International Journal of Environmental Research and Public Health*, *16*(21), 4202.

Stone, C., & Stone, D. L. (2015). Factors affecting hiring decisions about veterans. *Human Resource Management Review*, *25*(1), 68-79.

Tross, S. A., & Maurer, T. J. (2008). The effect of coaching interviewees on subsequent interview performance in structured experience-based interviews. *Journal of Occupational and Organizational Psychology*, *81*(4), 589-605.

United States Bureau of Labor Statistics (2020). *Employment situation of veterans news release*. https://www.bls.gov/news.release/vet.htm

United States Census Bureau (2020). *Veteran status*. https://data.census.gov/cedsci/table?q=veterans&tid=ACSST1Y2019.S2101

United States Department of Labor (2022). *Transition assistance program*. https://www.dol.gov/agencies/vets/programs/tap

Vespa, J. E. (2020). *Those who served: America's veterans from World War II to the War on Terror*. https://www.census.gov/library/publications/2020/demo/acs-43.html

Evolutionary Dynamics of Strategic Alliances in the Turkish Construction Industry: A Longitudinal Study

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Abstract

Strategic alliances, especially in project-based industries, are not only prevalent but also crucial for firms to meet market demands and maintain a long-term competitive edge. These cooperative organizational forms are frequently adopted in the construction industry, particularly for complex projects with high costs, risks, and the need for innovative solutions. Social network analysis (SNA) is a widely used research approach in organizational studies, offering insights into the nature and patterns of cooperative organizational forms like strategic alliances. This research delves into the concepts of the "depth" and "breadth" of strategic alliances in the construction industry using SNA. The relational dimension in the alliance network, such as the intensity and strength of relationships, represents the "depth" of strategic alliances, while the diversity dimension, including technical and geographical variations of alliance projects, signifies the "breadth" of strategic alliances. By employing "three different time windows," Social Network Analysis is used to investigate the patterns and nature of strategic alliances in the Turkish construction industry. The research findings, which are of significant importance, reveal that the pattern and nature of strategic alliances in the Turkish construction industry are dynamic and evolving due to the changes in the environment.

***Keywords**: competition and cooperation, construction industry, longitudinal study, social network analysis, strategic alliances.*

Introduction

In the rapidly evolving business environment, construction companies are increasingly turning to strategic alliances to stay competitive within project-based industries. These strategic alliances, often including collaborations with competitors, are not just beneficial but crucial for pooling resources, scaling operations, and accessing new markets. As noted by several scholars (Dyer et al., 2001; Ireland et al., 2002), such partnerships enhance competitive positioning while mitigating risks and fostering value creation through improved knowledge management, internal coordination, and increased visibility. The academic literature has expanded from a focus on bilateral relationships to a broader social network perspective, highlighting how strategic network connections influence decisions about partner selection, collaboration frequency, and contract types (Gulati, 1998). Social Network Analysis (SNA) has become essential for mapping the complex web of relationships in construction project management (CPM), underscoring the importance and complexity of these relationships (Borgatti & Halgin, 2011; Dogan et al., 2015; Zheng et al., 2016). This study addresses the gap in longitudinal understanding of how strategic alliances evolve within the Turkish construction industry. Utilizing a dual analytical framework, this research evaluates the "*depth*" and "*breadth*" of strategic alliances. "*Depth*" focuses on the quality and strength of partnerships, indicating the intensity of connections and the extent of resource sharing (Kale et al., 2002). "*Breadth*" assesses the diversity of a firm's external connections across different partners, sectors, and geographies, illustrating how firms handle technical and geographical challenges (Gulati, 1998).

Strategic Alliances

Strategic alliances are becoming increasingly important in the construction industry due to globalization and the need to address sector-specific challenges (Hameed & Abbott, 2017). The complexity of construction projects often necessitates the formation of alliances, which allow for the acquisition of a wide range of knowledge and skills. The literature identifies several motivations for forming construction alliances, including access to technology, risk sharing, securing financing, entering new markets, and improving competitive positions (Badger & Mulligan, 1995). Strategic alliances are generally defined as inter-organizational collaboration in business management. They can be categorized into two types based on the duration of the collaboration: strategic alliances and project alliances (Rowlinson et al., 2006). The latter is more common in the construction sector because construction projects are usually done on a project-by-project basis. These alliances are generally formed to share risks and responsibilities, aiming to enhance efficiency, especially in complex and high-risk projects (Ngowi, 2007; Chen et al., 2012). Chen et al. (2012) summarize the principles of successful alliancing, which include team selection based on competence, joint project proposal development, shared risk and reward, collective governance and management, and a commitment to open and honest communication. According to Ngowi (2007), careful partner selection and governance structures are influenced by factors such as complementarity, status similarity, prior experience, reputation, and trust. Trust and commitment are considered the most critical success factors for successful alliances. Studies concerning the effectiveness and prosperity of construction alliances have relied on both financial and operational metrics. These studies have highlighted the difficulties in reaching an agreement on performance assessment (Sillars & Kangari, 2004). In today's rapidly shifting technological and economic environment, strategic partnerships are increasingly utilized to achieve this end. Consequently, the construction industry has turned towards collaboration, primarily through alliances, as an appealing strategy to deal with issues such as low productivity, delays, disputes, and budget overruns (Chen et al., 2012). In summary, alliances in the construction sector are necessary to acquire a wide range of knowledge and skills in today's ever-changing technological and economic environment. Careful partner selection, shared objectives, and effective communication and governance mechanisms are crucial to successful collaboration.

Social Network Analysis and Strategic Alliances

Social network analysis (SNA) offers a comprehensive framework to understand the dynamics within social structures, emphasizing the complex web of relationships that underlie these systems. This approach is particularly relevant in the study of strategic alliances within project-based industries marked by complexity and competition. By examining the patterns of relationships among actors, network theory, as discussed by Emirbayer and Goodwin (1994), goes beyond traditional sociological approaches that view social behavior as the sum of individual actions. The concepts of ties and their strength are central to the network theory, as they represent the nature of relationships between actors within a network. Granovetter's (1973) seminal work on the strength of ties highlights that the depth of a relationship depends on several factors, such as interaction frequency, emotional depth, and mutual exchange of information. This perspective is crucial for understanding how strategic alliances form and evolve, emphasizing the role of both strong and weak ties in facilitating information flow and resource sharing. The application of network theory, and specifically the concept of social embeddedness, provides a robust theoretical foundation for analyzing strategic alliances. This focus on the social context in which economic and organizational decisions are made highlights the importance of considering the intricate web of social relationships in the study of strategic alliances.

Empirical Setting

This study delves into the Turkish construction industry, which is described as a temporary network-based organization with diverse social groups. It emphasizes the role of alliances in boosting productivity and performance through three distinct phases. From 1990 to 2000, Turkish contractors engaged in major infrastructure projects with foreign partners, enhancing their capabilities in production, project management, and international finance. The following decade saw expanded collaborations, increasing Turkey's presence in the global construction market. Since 2010, significant investments in major projects have boosted the sector's profitability. However, economic challenges in 2018 and subsequent policy shifts in 2019 adversely impacted the industry (TMB Construction Sector Analysis, 2019; INTES Construction Sector Report, 2019). This research highlights how strategic business alliances have evolved within the Turkish construction industry from 1990 to 2019, offering crucial insights into their dynamic nature.

Samples and Data Collection

This study analyzes strategic alliances of Turkish contractors listed in ENR-Turkey or affiliated with INTES or TCA (TMB), covering projects from 1990 to 2019. It focuses on the top 300 construction companies engaging with Turkish public institutions and significant international players linked with TCA or INTES. Selection criteria required firms to have been active since 1990 and involved in at least five alliance projects, delineating the alliance network for detailed analysis. Data was sourced from EKAP, ENR-Turkey, CSN databases, INTES, TCA, company websites, and EMIS, with EKAP providing key tender information. Employing network analysis at the inter-organizational level, the study examines 129 primary contractors and their partners, revealing the impact of domestic and international alliances on the Turkish construction industry's dynamics through a comprehensive exploration of the underlying relational network.

Operationalization

Alliance Breadth Dimension

The "*breadth*" dimension of alliance networks emphasizes the extensive external relationships a company maintains across a variety of partners, sectors, and geographic regions. *Breadth* is critical for accessing a diverse range of resources and knowledge, essential for integrating new technologies and optimizing resource use across projects (Gulati, 1998; Miller, 2006). Additionally, geographic diversity expands a firm's international reach, vital for entering new markets and driving innovation (Hanson et al., 2016). Despite challenges, this diversity promotes significant learning and adaptation.

In this study, *breadth* is measured through three indicators: the *Number of Partners*, *Project Types*, and *Geographic Locations*. These metrics assess the size of a company's network, the variety of projects undertaken, and the geographic spread. Projects are categorized into 15 distinct activities, and locations are evaluated to reflect the international expansion of Turkish construction firms since the 1970s. These measures collectively offer a comprehensive view of how firms leverage their extensive networks to succeed in competitive markets, highlighting the strategic use of alliances to boost operational capabilities and market position. This methodology underscores the importance of broad, diverse alliances in fostering industry success and innovation.

Table 1. Field of activity categories.

Technical Category	**Field of Activity**
1	Infrastructure Projects
2	Dams and HES Projects
3	Industrial Buildings
4	Airports
5	Harbors and Ports
6	Superstructures
7	Maintenance and Renewal
8	Mining Projects
9	Energy Plants
10	Metro and Light rail systems
11	Irrigation Works and Ponds
12	Land Reconstruction and Land
13	Landscaping Projects
14	Mechanical Works
15	Telecommunication Works

Table 2. Geographic Categories.

Geographical Category	**Region**
1	Turkey
2	Middle East, North Africa, and Non-EU-Member
3	Russian Federation, Turkic Republics, and Central Asia
4	Africa (North Africa is omitted)
5	Ireland and EU-Member European Countries
6	The Continent of America and other Island Countries

Alliance Depth Dimension

The "*depth*" dimension within network theory scrutinizes the quality, intensity, and strength of relationships between partnering organizations, emphasizing robust, trust-based relationships that develop through repeated interactions. *Depth* assesses the profound engagement and mutual investment of resources such as capital, technology, and knowledge, reflecting deeper, more integrated alliances (Kale et al., 2002). This dimension contrasts with breadth, which focuses on the range and diversity of connections.

In this study, *depth* is operationalized through three metrics: *Total Number of Repeated Ties, Technical Depth,* and *Geographic Depth*. *Total Number of Repeated Ties* measures ongoing satisfaction and trust that emerge from continuous partnerships, indicating strong relational bonds. *Technical Depth* is evaluated using Blau's Heterogeneity Index, traditionally a measure of diversity, adapted here to assess dispersion across different project types a firm engages in. The formula 1- $\sum_{i=0}^{k} pi^2$ is the proportion of projects in the i*th* category, gauges the intensity of focus on specific technical fields.

Geographic Depth applies Blau's Index to quantify the intensity of a firm's operations across various geographic areas, emphasizing the depth of engagement rather than sheer diversity. This scale, ranging from 0 to 1, highlights deeper local engagement indicative of specialized knowledge, strong partnerships, or significant investments. Projects are precisely categorized by fields and locations, enabling detailed calculations of technical and geographical depth scores. This innovative application of Blau's Index, aligning with prior research by Dhanaraj and Parkhe (2006) and Lavie and Rosenkopf (2006), underscores the critical role of deep, stable relationships in boosting the effectiveness of strategic alliances.

Data Processing

This research conducts an in-depth analysis of the Turkish construction industry's alliance network from 1990 to 2019, examining 129 firms that participated in at least five partnerships during their operational lifespan. Data across various Excel sheets were meticulously consolidated and corrected for typographical errors to ensure accuracy. The firms were categorized into "*primary firms*," specifically the 129 directly studied, and "*secondary firms*," which included partners not listed or associated with the referenced institutions, comprising a network of 736 firms. The analysis utilized numerical codes and pivot tables to distill relationships into binary pairs, allowing for the computation of key metrics like the Total Number of Partners and the Total Number of Ties. The study delved into recurring interactions among firms, highlighting the durability and intensity of these corporate relationships. Projects were categorized by field of activity and geographic location, employing Blau's Heterogeneity Index to measure depth across 15 activity types and 6 regions, providing detailed insights into each firm's depth in these areas. Data synthesis involved calculating breadth by averaging counts of partners, project types, and geographic locations for each period. Depth was similarly assessed by averaging metrics of repeated ties, technical depth, and geographic depth. An arithmetic mean across all periods facilitated a comparative analysis of average depth and breadth, offering comprehensive insights into the dynamics and factors contributing to the firm's success over time.

Research Findings

This research provides an in-depth analysis of the operational strategies among Turkish construction firms over three decades, highlighting significant changes in average *breadth* and *depth* that illustrate how these firms diversified operations and deepened partnerships.

1990-1999: Emergence and Foundation of Strategic Alliances

During the early 1990s, propelled by economic reforms and foreign investments, the Turkish construction industry started forming strategic alliances, primarily with international partners, for significant infrastructure projects. These early alliances were exploratory, focusing on enhancing capabilities and risk-sharing.

Group Analysis: The network comprised 30 primary contractor firms. High-depth and high-breadth firms were well-established entities managing extensive projects both domestically and internationally. Moderately positioned firms, with fewer partners and a narrower focus, aimed to grow internationally, whereas low-depth, low-breadth firms concentrated on local projects and formed new partnerships without international ventures.

2000-2009: Expansion and Diversification

This period witnessed expansion among 67 contractor firms, both domestically and internationally, driven by Turkey's strong economic performance. The strategic focus shifted toward deepening existing relationships and penetrating new markets like the Middle East and Turkic republics.

Group Analysis: Leading firms enhanced their engagements, tackling diverse, complex international projects with sustained partnerships. Moderately positioned firms dynamically pursued various international projects without renewing old alliances, while new entrants and lower-tier firms sought to expand their network presence.

2010-2019: Strategic Consolidation and Global Recognition

The most recent decade saw 127 firms concentrating on mega projects that demanded significant technical collaboration. Economic challenges around 2018 led to a shift toward more sustainable and efficient practices.

Group Analysis: Despite overall network growth, only a few firms remained in the high-depth, high-breadth group, which is indicative of market consolidation, where only select companies managed high diversification levels. These firms continued to strengthen their strategic positions through deep, lasting relationships and advanced projects, pushing further international expansion. Most firms achieved balanced growth, while an increase in low-depth, low-breadth firms suggested new industry entrants or firms specializing in niche areas. Over these thirty years, the strategic alliances in the Turkish construction industry evolved from initial exploratory stages to mature, integrated engagements deeply and broadly connected. Influenced by external economic factors, policy changes, and strategic decisions, successful firms enhanced their competitive edge and established leadership both domestically and internationally. This study highlights the importance of strategic flexibility and maintaining long-term relationships in the volatile construction industry, emphasizing how strategic alliances foster growth, enhance capabilities, and expand market reach.

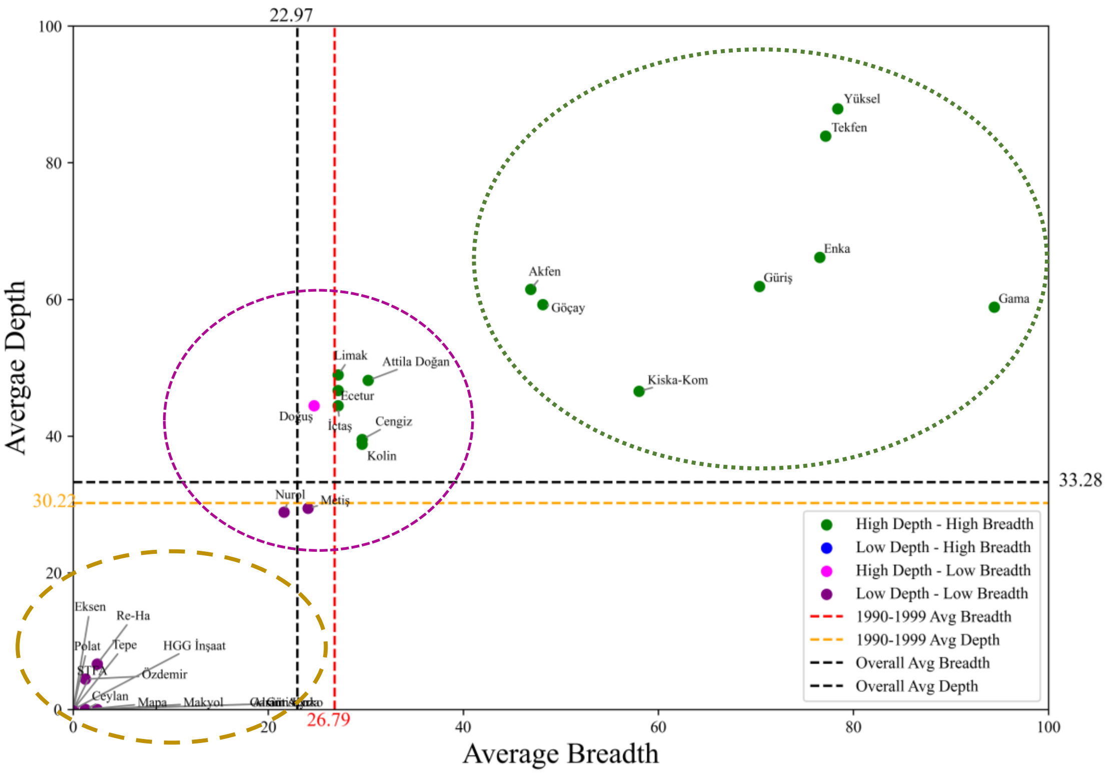

Figure 1(a): 1990-1999 period.

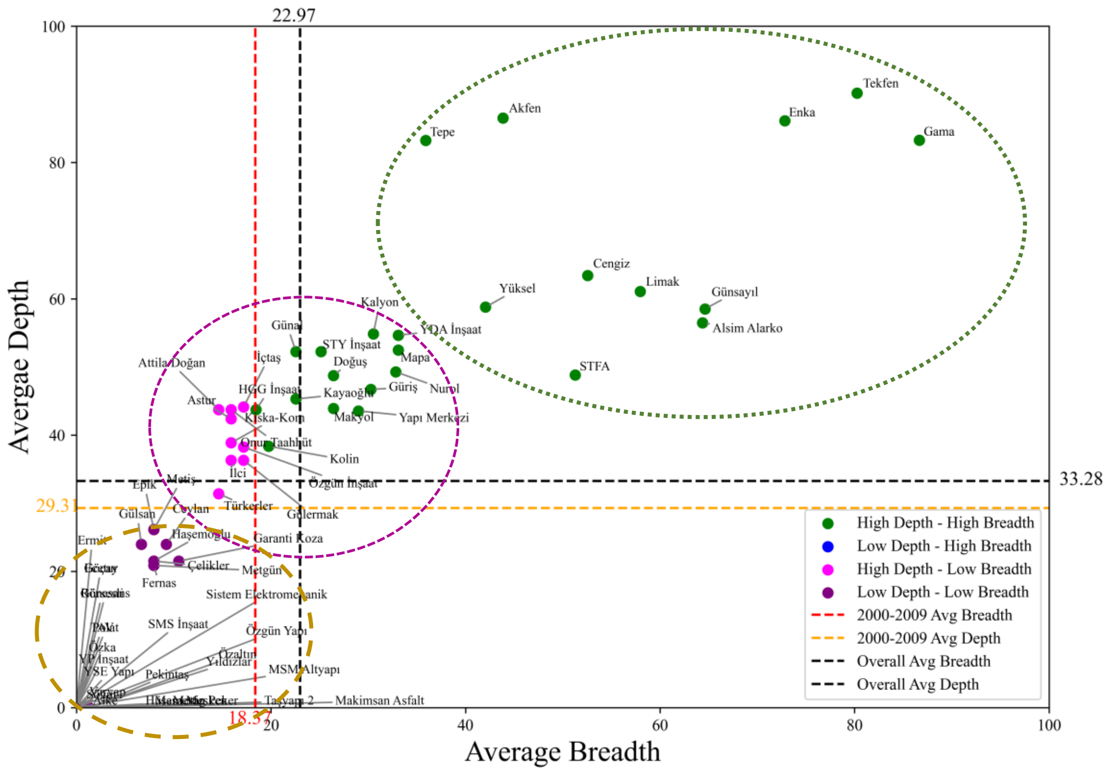

Figure 1(b): 2000-2009 period.

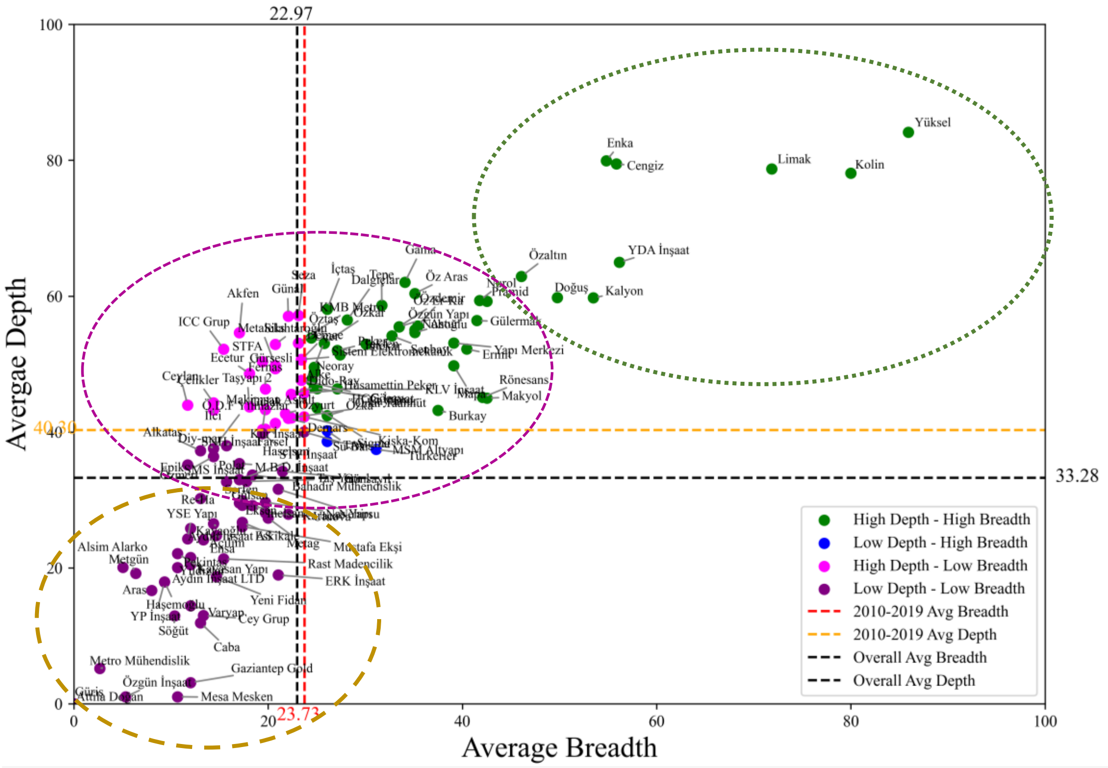

Figure 1(c): 2010-2019 period.

Figure 1**:** Graphic display of three periods of project alliances in the Turkish construction industry based on average depth and average breadth.

Discussion

This study explores the evolution of the alliance network among Turkish contractors from 1990 to 2019, charting significant shifts in the construction sector over three decades. By utilizing a longitudinal approach, the research uncovers patterns and trends in alliance dynamics that transcend simple snapshots, illustrating how changes in inter-organizational networks profoundly influence firm behavior and performance. The study leverages Blau's heterogeneity index to measure the *depth* of strategic alliances, demonstrating the innovative application of traditional diversity-focused measures in network analysis. This methodology offers valuable insights into the qualitative *depth* impacting strategic outcomes. Furthermore, the research provides empirical evidence that enriches network theory by showing how strategic alliances adapt to internal decisions and external economic forces. This dual focus not only extends the theoretical base of network theory but also equips industry practitioners with practical frameworks to optimize and enhance their strategic alliance capabilities, especially under resource constraints.

Limitations and Future Research Directions

This study provides an in-depth analysis of the Turkish construction industry, offering insights specifically tailored to its unique geographical and industry contexts. While robust for the Turkish construction sector, the findings' applicability to other industries or cultural settings may require further validation due to distinct contextual factors. The research utilizes Blau's index, traditionally for measuring diversity, to assess the *depth* of technical or geographical aspects of alliances, showcasing its versatility in exploring network dynamics. Incorporating additional measures like centrality and structural holes could enhance this analysis further. Challenges such as fluctuating data availability, evolving industry practices, and external factors like rapid technological changes and economic fluctuations highlight the complexity of this longitudinal study. This research underscores the strategic importance of alliances in project-based industries. It suggests further exploration to enhance the understanding of strategic alliances across various contexts, providing valuable insights for both practitioners and scholars.

Conclusion

This longitudinal study analyzes the depth and breadth of strategic alliances in the Turkish construction industry to reveal their evolving dynamics. It enriches our understanding of alliance dynamics and provides strategic insights for navigating complex project environments. The research highlights the importance of developing robust, adaptive alliances. It suggests that future studies should expand cross-industry applications and integrate broader network analytical tools to unravel further the complexities of strategic alliances as the industry faces ongoing changes and challenges.

References

Badger, W. W., & Mulligan, D. E. (1995). Rationale and benefits associated with international alliances. *Journal of Construction Engineering and Management, 121*(1), 100-111.

Borgatti, S. P., & Halgin, D. S. (2011). On network theory. *Organization Science*, *22*(5), 1168-1181.

Chen, G., Zhang, G., Xie, Y. M., & Jin, X. H. (2012). Overview of alliancing research and practice in the construction industry. *Architectural Engineering and Design Management*, *8*(2), 103-119.

Dhanaraj, C., & Parkhe, A. (2006). Orchestrating innovation networks. *Academy of Management Review*, *31*(3), 659-669.

Dogan, S. Z., Arditi, D., Gunhan, S., & Erbasaranoglu, B. (2015). Assessing coordination performance based on centrality in an e-mail communication network. *Journal of Management in Engineering*, *31*(3), 04014047.

Dyer, J. H., Kale, P., & Singh, H. (2001). Strategic alliances work. *MIT Sloan Management Review*, *42*(4), 37-43.

Emirbayer, M., & Goodwin, J. (1994). Network analysis, culture, and the problem of agency. *American Journal of Sociology, 99*(6), 1411-1454.

Granovetter, M. S. (1973). The strength of weak ties. *American Journal of Sociology, 78*(6), 1360-1380.

Gulati, R. (1998). Alliances and networks. *Strategic Management Journal*, *19*(4), 293-317.

Hameed, W., & Abbott, C. (2017). *Critical review of the success factors of strategic alliances in the UK construction industry*.

Hanson, D., Hitt, M. A., Ireland, R. D., & Hoskisson, R. E. (2016). *Strategic management: competitiveness and globalisation*. Cengage.

Ireland, R. D., Hitt, M. A., & Vaidyanath, D. (2002). Alliance management as a source of competitive advantage. *Journal of Management*, *28*(3), 413-446.

Kale, P., Dyer, J. H., & Singh, H. (2002). Alliance capability, stock market response, and long-term alliance success: the role of the alliance function. *Strategic Management Journal*, *23*(8), 747-767.

Lavie, D., & Rosenkopf, L. (2006). Balancing exploration and exploitation in alliance formation. *Academy of Management Journal*, *49*(4), 797-818.

Miller, D. J. (2006). Technological diversity, related diversification, and firm performance. *Strategic Management Journal*, *27*(7), 601-619.

Ngowi, A. B. (2007). The role of trustworthiness in the formation and governance of construction alliances. *Building and Environment*, *42*(4), 1828-1835.

Rowlinson, S., Cheung, F. Y., Simons, R., & Rafferty, A. (2006). Alliancing in Australia—No-litigation contracts: a tautology? *Journal of Professional Issues in Engineering Education and Practice, 132*(1), 77-81.

Sillars, D. N., & Kangari, R. (2004). Predicting organizational success within a project-based joint venture alliance. *Journal of Construction Engineering and Management, 130*(4), 500-508.

Zheng, X., Le, Y., Chan, A. P., Hu, Y., & Li, Y. (2016). Review of the application of social network analysis (SNA) in construction project management research. *International Journal of Project Management*, *34*(7), 1214-1225.

Motivation in Design Offices with Herzberg's Two-Factor Theory

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Abstract

Today, suitability of the working environment for the employees has a great impact on their job satisfaction and motivation. Motivation and job satisfaction are the factors employers should pay attention for the success of their organization. In organizational terms, motivation is the association of employees' goals and expectations with the organization's and, as a result have a beneficial effect on both parties. Creation of work environments, satisfying both psychological and physical health of employees is important for the productivity of the organization and improving employee performance. The objective of this study is comparing motivations of architects working in two different cities in two different regions of Turkey based on the factors put forth by Frederick Herzberg in Two-Factor Theory. Herzberg identified two main factors in his theory, intrinsic (hygiene) factors such as proficiency on the job, success, recognition and appreciation and external factors such as working conditions and business policy. A survey technique used to reveal motivation of architects working in design offices in Istanbul and Gaziantep. The results showed that motivations of Gaziantep participants were better in most factors compared to Istanbul participants, and in this case, motivations of employees at architectural offices in Gaziantep was higher than Istanbul.

Keywords: *architect, design offices, Herzberg, Two-Factor Model*.

Introduction

Human side is an interesting aspect in the design offices as well as in other organizations. In difficult market conditions, employers should pay attention to the satisfaction, morale and motivation of the employees and the suitability of the working environment for them. Because the creation of working environment that satisfy both psychological and physical needs of employees will improve employee performance, productivity, and work commitment. Work related needs can change from employee to employee, and most of the time managers must motivate a diverse and, in many respects unpredictable group of people (Ivancevich et al., 2005). A powerful link exists between motivation and employees who have job satisfaction are expressing an attitude towards their job because of evaluating the characteristics of their job against their expectations. Hence, employees with job satisfaction are expected to be motivated to perform effectively (Walker, 2011).

Motivation is defined as the forces within a person that affect his or her direction, intensity, and persistence of voluntary behavior. Motivated employees are willing to exert a particular level of intensity for a certain amount of time (persistence), toward a particular goal (direction) (McShane & Von Glinow, 2000). Employees must have sufficient motivation to achieve work objectives even if they have clear work objectives, the right skills, and a supportive work environment (Walker, 2011).

This research is carried out to determine motivations of architects working in design offices within the frame of Frederick Herzberg's Two-Factors Theory. The objective of this study is comparing motivations of architects working in two different cities in two different regions of Turkey, which are Istanbul and Gaziantep.

Herzberg's Two-Factor Theory

Employees in organizations can be motivated in two ways, firstly motivating themselves by striving to embark on a task that brings satisfaction and gearing them in the achievement of their goals. Secondly, individuals in organizations can be motivated through environmental factors, such as increased pay, career advancement, commendation, and recognition (Ihensekien & Joel, 2023). In this light, Frederick Herzberg has identified two main factors in his theory and labeled the satisfiers motivators, and he called the dissatisfiers hygiene factors. Herzberg argued that the opposite of satisfaction is not dissatisfaction, but no satisfaction. In other words, satisfaction, and no satisfaction are located at the opposite ends of the same continuum (Hur, 2018). Table 1 shows intrinsic (hygiene) factors and extrinsic motivational factors of the theory. The term hygiene refers to factors that are preventive; in Herzberg's theory the hygiene factors are those that prevent dissatisfaction. Taken together, the motivators and the hygiene factors have been known as Herzberg's two-factor theory of motivation (Luthans, 2021).

Table 1. Herzberg's two factor theory.

Intrinsic factors	Extrinsic motivation factors
Competence at work	Wage
Success	Business policy and management
Recognition and appreciation	Working conditions
Career progress	Safety at work
Responsibility and autonomy	Interpersonal relationships
Development and promotion	Supervision

Herzberg proposed the Two-Factor Theory of Motivation, arguing that both satisfaction and dissatisfaction do not belong to the same dimension (Hur, 2018). Herzberg proposed motivators related to job satisfaction, such as achievement, recognition, responsibilities, advancement, growth, work itself, and hygiene factors as preventing job dissatisfaction, including company policy and administration, job security, salary, supervision, interpersonal relationships, supervisory relationships, physical working condition, and benefit. According to Herzberg, the absence of motivators does not necessarily lead to job dissatisfaction, and the preferred level of hygiene factors does not necessarily result in job satisfaction. Therefore, job satisfaction and dissatisfaction are not elements of a single continuum (Thant & Chang, 2021). Hygiene factors are related to working conditions and environments such as salary, benefits, interpersonal relationships, and company policies (Hur, 2018). Two-factor theory of motivation has given rise to a mass of investigations and experiments in industry and in many different types of organizations. Results do not always support Herzberg; in fact, only about one in three do so (Gardner, 1977).

Research Method

The research focused on measuring motivations of architects working in architectural design offices in Istanbul and Gaziantep within the frame of Herzberg's Two-Factor Theory. A survey technique was used to reveal the thoughts of architects working in design offices. A 5-point Likert Scale was used in the survey. 157 architects replied question paper which 99 of the participants are from Istanbul and 58 are from Gaziantep. A questionnaire was designed to solicit information about the motivation levels of architects. The unit of analysis for the study was the employee architects working in architectural design offices. Questionnaire was prepared in Google Form. A cover letter and the questionnaire form were sent via e-mail. The cover letter explained the academic purpose of the research and assured confidentiality. The survey method was used as the research method. Statistical analyses of the data in the study were performed using the IBM Spss 25.0 version.

The questionnaire consists of two sets of questions. The first set of questions was designed to provide data related to the characteristics of the architects and the offices they are working. The second set of questions was designed to provide data for measuring motivation levels of architects. External factors are divided into three groups which are working conditions, business policy and supervision and interpersonal relationships. External motivation factors were measured with 17 questions. Intrinsic factors are, also, divided into three groups. The first group is competence at work, success, recognition, and appreciation. The second one is responsibility and autonomy, and the third one is interest, career advancement and development. Intrinsic motivation factors were measured with 16 questions. The respondents were asked to indicate their answers by using a five-point Likert-type scale, where 1 = never, 2 = rarely, 3 = sometimes, 4 = often, and 5 = always.

Results

Table 2 provides gender, marital status, and age of the architects. According to the results the gender proportions of the respondent architects were not distributed equally: 61 (61.6%) were women, whereas 38 (38.4%) were men in Istanbul and 40 (69.0%) were women, whereas 18 (31.0%) were men in Gaziantep. The results showed that most of the architects working in architectural design offices are women both in Istanbul and Gaziantep. Most of the architects working in architectural design offices are between 22 and 30 years old (89.9% in Istanbul and 93.1% in Gaziantep), single (88.9% in Istanbul and 79.3% in Gaziantep) and graduated between 1 and 5 years before (89.9 in Istanbul and 86.2% in Gaziantep). When the results are compared, architects working in architectural design offices in Istanbul and Gaziantep, have common properties. Employee architects are in their first years of professional life.

Table 2. Gender, marital status, age, and graduation years of architects.

		Istanbul Number of architects	%	Gaziantep Number of architects	%
Gender	Women	61	61.6	40	69.0
	Men	38	38.4	18	31.0
Marital status	Married	11	11.1	12	20.7
	Single	88	88.9	46	79.3
Age	22-25	43	43.4	37	63.8
	26-30	46	46.5	17	29.3
	31≥	10	10.1	4	6.9
Graduation year	1-2 years	44	44.4	20	34.5
	3-5 years	45	45.5	30	51.7
	6≥years	10	10.1	8	13.8
Total		99	100.0	58	100.0

Table 3 provides number of works and working years of the architects. According to the results most of the architects are in their 1st job in Istanbul (43.4%), however in Gaziantep most of the participants are in their 2nd job (51.7%). The results showed that most of the architects have been working for 2 to 4 years (42.4%) in Istanbul, however in Gaziantep most of the participants have been working for 1-4 years (81.1%). The results highlight that, most of the architects have started their professional life less than 4 years ago in Gaziantep, however most of them are working in their 2nd job.

Table 3. Number of works and working years of the architects.

		Istanbul Number of architects	%	Gaziantep Number of architects	%
Number of works	1st job	43	43.4	19	32.8
	2nd job	26	26.3	30	51.7
	3≥ job	30	30.3	9	15.5
Number of working years	0-1 year	37	37.4	24	41.4
	2-4 years	42	42.4	23	39.7
	5≥ years	20	20.2	11	19.0
Total		99	100	58	100

Table 4 provides the relationship between external motivation factors and age of the architects. According to the results, when we compare external factors, working conditions satisfaction of all participants, was 3.45 out of 5 in Istanbul and 3.72 in Gaziantep. When we compare external factors, business policy satisfaction of all participants, was 3.20 in Istanbul and 3.39 in Gaziantep. When we compare external factors, supervision, and interpersonal relationships satisfactions of all architects, was 3.74 in Istanbul and 3.86 in Gaziantep. Architects working in Gaziantep were more satisfied with external motivation factors than in Istanbul. When we compare age groups separately, satisfaction of architects in working conditions in Istanbul are around 3.4 for every age group, however in Gaziantep especially architects older than 31 have the highest satisfaction. Architects older than 31 have the least business policy satisfaction in Istanbul (2.92), however in Gaziantep have the highest satisfaction (3.89). Architects older than 31 have the least supervision and interpersonal relationship satisfaction in Istanbul (3.58), however in Gaziantep have the highest satisfaction (4.35). The results highlight that, architects older than 31 in Gaziantep have the highest satisfaction in external motivation factors, however in Istanbul 22 to 25 years old architects are more satisfied with working conditions, 26-30 years old architects are more satisfied with business policy and 22-30 years old architects are more satisfied with supervision and interpersonal relationships.

Table 4. External motivation factors and age of architects.

	Age	Istanbul Number of architects	X	Gaziantep Number of architects	X
Working conditions	22-25	43	3.4942	37	3.6014
	26-30	46	3.4185	17	3.7206
	31≥	10	3.4500	4	4.7500
	Total	99	3.4545	58	3.7155
Business policy	22-25	43	3.2196	37	3.2973
	26-30	46	3.2391	17	3.4575
	31≥	10	2.9222	4	3.8889
	Total	99	3.1987	58	3.3851
Supervision and interpersonal relationships	22-25	43	3.7628	37	3.7459
	26-30	46	3.7609	17	4.0118
	31≥	10	3.5800	4	4.3500
	Total	99	3.7434	58	3.8655

Table 5. External motivation factors and number of jobs of the architects.

	Working years	Istanbul Number of architects	X	Gaziantep Number of architects	X
Working conditions	1st job	43	3.4709	19	3.7237
	2nd job	26	3.3173	30	3.7667
	3≥ job	30	3.5500	9	3.5278
	Total	99	3.4545	58	3.7155
Business policy	1st job	43	3.2661	19	3.4444
	2nd job	26	3.0385	30	3.3741
	3≥ job	30	3.2407	9	3.2963
	Total	99	3.1987	58	3.3851
Supervision and interpersonal relationships	1st job	43	3.7767	19	3.9263
	2nd job	26	3.5846	30	3.8733
	3≥ job	30	3.8333	9	3.7111
	Total	99	3.7434	58	3.8655

Table 5 provides the relationship between external motivation factors and number of jobs of the architects. According to the results, working conditions satisfaction of architects who are working in their 3rd or more jobs in Istanbul have highest satisfaction (3.55), however in Gaziantep especially architects working in their 2nd job have the highest satisfaction (3.76). Architects working in their 1st job have the highest business policy satisfaction in Istanbul (3.27), similarly in Gaziantep, architects working in their 1st job, also, have the highest satisfaction (3.44). Architects who are working in their 2nd job have the least supervision and interpersonal relationships satisfaction in Istanbul (3.58), however in Gaziantep, architects who are working in their 3rd or more job have the least satisfaction (3.71). The results showed that architects who are working in their 3rd or more jobs in Istanbul were more satisfied with working conditions and supervision and interpersonal relationships, however architects who are working in their 1st job are more satisfied in business policy. On the other hand, in Gaziantep architects who are working in their 2nd job are more satisfied with working conditions, architects who are working in their 1st job are more satisfied with business policy and supervision and interpersonal relationships.

Table 6. Intrinsic motivation factors and age of architects.

	Age	Istanbul Number of architects	X	Gaziantep Number of architects	X
Competence at work, success, recognition and appreciation	22-25	43	3.6227	37	3.6336
	26-30	46	3.7222	17	3.9085
	31≥	10	3.4667	4	4.4167
	Total	99	3.6532	58	3.7682
Responsibility and autonomy	22-25	43	3.5349	37	3.3716
	26-30	46	3.7609	17	3.8088
	31≥	10	3.2500	4	4.2500
	Total	99	3.6111	58	3.5603
Interest, career advancement and development	22-25	43	3.7829	37	3.3784
	26-30	46	3.9638	17	3.6863
	31≥	10	3.4667	4	4.5000
	Total	99	3.8350	58	3.5460

Table 6 provides the relationship between intrinsic motivation factors and age of the architects. According to the results, when we compare intrinsic motivation of architects, competence at work, success, recognition, and appreciation, was 3.65 out of 5 in Istanbul and 3.77 in Gaziantep. Responsibility and autonomy of architects was 3.61 in Istanbul and 3.56 in Gaziantep. İnterest, career advancement and development were 3.84 in Istanbul and 3.55 in Gaziantep. When we compare intrinsic motivations of architects, those working in Gaziantep were more satisfied with competence at work, success, recognition, and appreciation than in Istanbul, however architects working in Istanbul are more satisfied with responsibility and autonomy and interest, career advancement and development. When we compare groups separately, satisfaction of architects who are 31 years old and more in Istanbul have the least, however in Gaziantep especially architects older than 31 have the highest satisfaction. When we compare groups separately, architects who are between 26 and 30 years old have the highest satisfaction in competence at work, success, recognition and appreciation (3.72) in Istanbul, however in Gaziantep architects who are older than 31 have the highest satisfaction (4.42).

When we compare groups separately, architects older than 31 have the least responsibility and autonomy satisfaction in Istanbul (3.25), however in Gaziantep have the highest satisfaction (4.25). Architects older than 31 have the least interest, career advancement and development satisfaction in Istanbul (3.47), however in Gaziantep have the highest satisfaction (4.50). The results highlight that, architects older than 31 in Gaziantep have the highest satisfaction in intrinsic motivation factors.

Table 7. Intrinsic motivation factors and number of works of architects.

	Working hours	Istanbul Number of architects	X	Gaziantep Number of architects	X
Competence at work, success, recognition and appreciation	1st job	43	3.6537	19	3.6082
	2nd job	26	3.5940	30	3.7556
	3≥ job	30	3.7037	9	4.1481
	Total	99	3.6532	58	3.7682
Responsibility and autonomy	1st job	43	3.5988	19	3.3553
	2nd job	26	3.6250	30	3.6333
	3≥ job	30	3.6167	9	3.7500
	Total	99	3.6111	58	3.5603
Interest, career advancement and development	1st job	43	3.7907	19	3.5614
	2nd job	26	3.7949	30	3.5111
	3≥ job	30	3.9333	9	3.6296
	Total	99	3.8350	58	3.5460

Table 7 provides the relationship between intrinsic motivation factors and number of jobs of the architects. The results show that, competence at work, success, recognition, and appreciation satisfaction of architects who were working in their 3rd or more job was higher than the other groups in Istanbul (3.70), and similarly in Gaziantep (4.15). Responsibility and autonomy satisfaction of architects who are working in their 2nd job have the highest responsibility and autonomy satisfaction in Istanbul (3.63), however in Gaziantep, architects who are working in their 3rd or more jobs have the highest satisfaction (3.75). Architects who are working in their 3rd or more jobs have the highest interest, career advancement and development satisfaction in Istanbul (3.93), similarly in Gaziantep, the same group has the highest satisfaction (3.63). The results highlight that, architects who are working in their 3rd or more jobs were more satisfied with competence at work, success, recognition and appreciation and interest, career advancement and development factors, but architects who are working in their 2nd job have higher satisfaction with responsibility and autonomy in Istanbul. On the other hand, architects who are working in their 3rd or more jobs in Gaziantep have the highest satisfaction with all intrinsic motivation factors.

Conclusion

Within the frame of this research, motivations of architects working in architectural design offices in Istanbul and Gaziantep were measured through the view of Frederick Herzberg's

Two-Factors Theory. The objective of this study is comparing motivations of architects working in two different cities in two different regions of Turkey.

The results obtained within the frame of this study were just like obtained by Matei and Abrudan (2016) which the main conclusion of their research was that, as formulated by Herzberg and his colleagues, the Two Factor Theory was not appropriate for the cultural context of Romania, which supports Gardner (1977). As a result of the survey conducted within the framework of Herzberg's theory and on the selected sample, it was revealed that external factors are at least as important as internal factors. Both external motivation factors (working conditions, business policy, supervision, and interpersonal relations), and intrinsic motivation factors (competence at work, success, recognition and appreciation, responsibility and autonomy, interest, career advancement and development) are meaningful both in Istanbul and Gaziantep, however satisfaction of architects were higher most of the time in Gaziantep than Istanbul. It was found that the motivation averages of Gaziantep participants were better in most factors compared to Istanbul participants, and in this case, motivations of employees working in architectural design offices in Gaziantep was higher than Istanbul.

References

Gardner, G. (1977). Is there a valid test of Herzberg's two-factor theory? *Journal of Occupational Psychology*, *50*(3), 197-204.

Hur, Y. (2018). Testing Herzberg's two-factor theory of motivation in the public sector: Is it applicable to public managers? *Public Organization Review*, *18*, 329-343. DOI: 10.1007/s11115-017-0379-1

Ihensekien, O. A., & Joel, A. C. (2023). Abraham Maslow's hierarchy of needs and Frederick Herzberg's two-factor motivation theories: Implications for organizational performance. *The Romanian Economic Journal*, *85*. DOI: 10.24818/REJ/2023/85/04

Ivancevich, J. M., Matteson, M. T., & Konopaske, R. (2005). *Organizational behavior and management.* Irwin/Mc-Graw-Hill, New York.

Luthans, F., Luthans, B. C., & Luthans, K. W. (2021). *Organizational behavior, an evidence-based approach.* Information Age Publishing., North Carolina.

Matei, M. C., & Abrudan, M. M. (2016). Adapting Herzberg's two factor theory to the cultural context of Romania. *Procedia-Social and Behavioral Sciences*, *221*, 95-104.

McShane, S. L., & Von Glinow, M. A. Y. (2000). *Organizational behavior* (p. 672). Irwin/McGraw-Hill, Boston.

Thant, Z. M., & Chang, Y. (2021). Determinants of public employee job satisfaction in Myanmar: Focus on Herzberg's two factor theory. *Public Organization Review*, *21*(1), 157-175. DOI: 10.1007/s11115-020-00481-6

Walker, A. (2011). *Organizational behavior in construction.* John Wiley & Sons/ Blackwell, West Sussex.

Mobbing in the Construction Sector: A Case Study of Türkiye

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Abstract

Mobbing, also known as work bullying, can be explained as physical and psychological violence as well as the pressure exerted by the employer or co-workers on a group of workers. Studies on mobbing have a growing interest around the globe in the last decade. In Türkiye, mobbing has also become an important issue in the working environment. The construction industry, which employs millions of people, also suffer from mobbing. Work bullying results in several clashes and problems on construction sites and even may lead to occupational diseases, work accidents, injuries, and deaths. In addition to the psychological, sociological, and physical effects, mobbing has also negative impacts on projects success, such as a decrease in work efficiency, cost overruns, and project delays. This study aims to investigate the impacts of mobbing on employees in the Turkish construction industry. The research utilized an electronic survey, which administered to 72 employees, who thought they were subjected to mobbing, in the construction industry. The survey data were analyzed with various statistical methods. The study showed that vertical mobbing, in which the mobber or victim has a higher position, is dominant in the Turkish construction industry. The study recommends that stakeholders should take necessary measures to mitigate mobbing problems to ensure the mental and physical health of employees as well as achieving project success by avoiding additional costs of mobbing.

Keywords: *mobbing, construction industry, psychological violence.*

Introduction

Psychosocial factors are important for workplace management as well as for the employee structure in an organization (Wahyudi Rahman et al., 2024). Mobbing is one of the most critical aspects, which is considered an extreme form of social stress in the workplace (Qureshi et al., 2013). Mobbing is the long-term systematic pressure exerted by people or groups in power on others through psychological means, especially in groups and organizations with a hierarchical structure and weak control (Ege, 1996; Erdoğan, 2009). In order for a behavior to be considered mobbing, it must be done frequently for a long time (at least six months) and even in an organized and gang-like manner, while the behavior is done by a single person, it is generally called 'bullying' (Leymann, 1996, Arpacıoğlı, 2024). It may not always be easy to distinguish mobbing from a normal conflict, sexual harassment, paranoia or any personality disorder, or workplace stress caused by excessive workload (Tınaz et al., 2008).

In the literature, there are several studies, which addressed the mobbing issue in construction industry in different aspects. Erdis et al. (2021) investigated the causes and types of mobbing in the construction industry, the perceptions and reactions of construction professionals regarding mobbing, and the effects of mobbing on the families and social lives of the victims. The results showed that construction professionals are aware of the concept of mobbing but do not know their rights. Greacen and Ross (2023) conducted a study examining workplace bullying by managers, particularly towards apprentices and trainees, in traditionally male-dominated industries such as the construction industry in Australia. In their study on employees who experienced permanent disability due to mental disorders in the construction industry, Kamardeen and Hasan (2023) determined that this situation occurred due to depression or anxiety along with stress, post-traumatic stress disorder resulting from various traumatic events, or exposure to traumatic events. workplace violence and bullying. Yokouchi et al. (2024) conducted a study to determine the prevalence of workplace bullying and harassment in the Japanese construction industry and its relationship with subjective health and job attractiveness. Kutkan and Atabay (2019) conducted a study to determine the effects of mobbing on work accidents and occupational diseases in the construction industry.

More than one in five workers (about 23%) experience physical, psychological or sexual distress at work, according to joint analysis of the International Labor Organization, Lloyd's Register Foundation (LRF) and Gallup (ILO, 2022). In a survey conducted on 103 academics at 5 universities in Türkiye, it was revealed that 12 academics were exposed to mobbing to varying degrees (Tigrel and Kokalan, 2009). Therefore, mobbing is an important and critical issue to be concerned in any industry. This study aims to examine the impacts of mobbing behaviors on employees in Turkish construction industry through a survey-based research. The study has tried to answer the following research questions:

1- What are the mobbing behaviors that the participants are most frequently exposed to?
2- What is the relationship between demographic characteristics such as gender, age, marital status, position, experience level and being exposed to mobbing?

Material and Method

The study administered an electronic survey, which involved 72 people who considered that they were subjected to mobbing working in the construction industry. The survey included a total of 30 questions. Five questions in the first group of the survey were prepared to understand the demographic characteristics of the participants, and 25 questions in the second group were prepared according to a 5-point Likert scale to determine the mobbing behaviors that the participants encountered.

Demographic information about respondents is shown in Table 1.

Table 1. Demographic profile of respondents.

Characteristics	Category	Number (N)	Percentage (%)
Gender	Male	54	75,00%
	Female	18	25,00%
		72	100,00%
Marital Status	Married	45	62,50%
	Single	27	37,50%
		72	100,00%
Age (years)	20-30	29	40,28%
	31-40	19	26,39%
	41-50	15	20,83%
	51 and above	9	12,50%
		72	100,00%
Position	Technical Staff (Engineer, Architect)	36	50,00%
	Chief or similar	15	20,83%
	Manager	12	16,67%
	Other	4	5,56%
		72	100,00%
Experience	1-5 years	32	44,44%
	6-10 years	11	15,28%
	11-15 years	2	2,78%
	16-20 years	8	11,11%
	21 years and above	19	26,39%
		72	100,00%

According to demographic data, one quarter of the respondents who participated in the survey are women and three fourth of those are men. The participants with age of between 20 and 30 years old constitue the majority of the sample. It can be said that the respondents are mostly young employees. According to marital status, 62.5% are single and 37.5% are married. This shows that there are more single participants in the survey. When we take into experience, the employees with experience between 1 and 5 years dominate the sample with 44.4%. It is also seen that the title of the majority of the people who responded to the survey is the technical staff (engineer, architect) with 53.7%.

After filtering the reliable the valid responses, the data obtained were analyzed through statistical tests, ANOVA, and t-tests.

Results and Discussion

Table 2 shows the ranking of the most common mobbing behaviors, that respondents have encountered. According to the results, participants have been highly exposed to mobbing behaviors, such as restricted ability to express themselves, being interrupted while speaking, and being forced to do undesired and inappropriate tasks. Table 3 indicates ANOVA and t-test results.

Table 2. Ranking of mobbing behaviors.

Phrase			Rank
Your ability to express yourself is restricted by your supervisors, colleagues or people you work with.	Mean	2,57	1
	S.D.	1,298	
You are constantly interrupted while speaking.	Mean	2,51	2
	S.D.	1,321	
You may be forced to do task that negatively affects your self-confidence.	Mean	2,39	3
	S.D.	1,369	
You are given jobs that are beyond your qualifications and require less skills than you have, which will lower your reputation in the institution you work for.	Mean	2,35	4
	S.D.	1,493	

Table 3. ANOVA and t-test results.

Characteristics	Category	Mean	S.D.	p-value (sig.)
Gender	Male	1,92	0,93	0.353
	Female	2,09	1,06	
Marital Status	Married	1,95	1,02	0.862
	Single	2,2	1,02	
Age (years)	20-30	2,15	1,02	0,020
	31-40	1,48	0,39	
	41-50	2,35	1,07	
	51 and above	2,42	1,46	
Position	Technical Staff (Engineer, Architect)	2,21	1,05	0,453
	Chief or similar	1,83	0,72	
	Manager	1,62	1,09	
	Other	1,75	2,42	
Experience	1-5 years	2,12	0,97	0,286
	6-10 years	1,58	0,72	
	11-15 years	1,22	0,14	
	16-20 years	2	0,98	
	21 years and above	2,3	1,23	

The relations between different parameters, such as gender, marital status, age, position, experience, and mobbing behaviors were investigated. A significant relationship was found between age and mobbing behaviors. The results show that young employees under 30 years old and employees above 40 years old are exposed to much mobbing than those who are between 30-40 years old. There was no significant relationship identified between other variables and mobbing behavior.

Considering the ranking of common mobbing behaviors and the results of statistical tests, the effects of vertical mobbing have been dominant. The main reasons for vertical mobbing, in which the mobber or the victim has a higher position can be a threat to social image, age difference, favoritism, and political reasons (Erdogan, 2009; Yavuz, 2013).

The study also revealed that employees who are above 40 years old are considerably subjected to mobbing. This is critical for the success of the construction sector in Türkiye. Mobbing has an increasing effect on unemployment, health expenditures, and insurance costs. Furthermore, early retirement demands of mobbing victims, loss of professional competence, and burnout bring additional costs to business life and the whole society (ÇSGB, 2013). In addition to the negative economic effects of mobbing, it is also inevitable that it will have extremely serious, direct and indirect social consequences. The psychological costs that mobbing brings to organizations can be conflicts between employees, a negative working environment, disputes in cultural values, distrust, lack of respect and team spirit, shortcomings in motivation and creativity (Tınaz, 2011).

Conclusion

Today, a large number of employees face different ways of mobbing in working life. This study investigated mobbing behaviors in the construction industry in Türkiye by administering a questionnaire survey. The results have shown that construction employees are mostly exposed to vertical mobbing behaviors due to the hierarchical structure of the construction industry. To avoid mobbing challenges, construction companies should take necessary measures to avoid additional costs due to potential increased insurance expenditures, early retirement demands, delays, lack of motivation, and clashes. In addition, mobbing is against human rights and any stakeholder in the construction industry should be respectful to others. The effects of psychological mobbing on the individual's mental and physical health are much worse than the economic and social effects.

This study has some limitations. The sample involved 72 employees and further research with a larger sample, and more variables would yield better outputs for understanding the current state of mobbing in the construction industry and determining potential measures.

References

Arpacıoğlu, G. (2024, April 10). *Mobbing Yardım*. https://mobbingyardim.wordpress.com/isyerinde-stresin-gizli-kaynagi-zorbalik-ve-duygusal-taciz/ (accessed on 24th January, 2024)

ÇSGB (2013). *İşyerinde Psikolojik Taciz Mobbing*. Yayın No:87, Ankara, www.sgk.gov.tr. (accessed on 24th January, 2024).

Ege, H. (1996). *Mobbing: che cos' è il terrore psicologico sul posto di lavoro*. Pitagora Editrice.

Erdis, E., Genç, O., & Aydınlı, S. (2021). Mobbing on construction professionals: causes, consequences, and precautions. *International Journal of Construction Management*, *21*(10), 987-996.

Erdoğan, G. (2009). Mobbing (işyerinde psikolojik taciz). *Journal of the Union of Turkish Bar Associations*, (83), 318-352.

Greacen, P., & Ross, V. (2023). Exploring the impact of social identity on the bullying of construction industry apprentices. *International journal of environmental research and public health*, *20*(21), 6980.

ILO, International Labour Organization (2022). *Experiences of violence and harassment at work: A global first survey.*

Kamardeen, I., & Hasan, A. (2023). Analysis of work-related psychological injury severity among construction trades workers. *Journal of Management in Engineering*, *39*(2), 04023001.

Kutkan, A., & Atabay, Ş., (2019). İnşaat sektöründe mobbing'in iş kazaları ve meslek hastalıklarına etkileri. *Mühendislik ve Multidisipliner Yaklaşımlar,* 216-247, Güven Plus Grup A.Ş. Publications. Istanbul, Türkiye.

Leymann, H. (1996). The content and development of mobbing at work. *European journal of work and organizational psychology*, *5*(2), 165-184.

Qureshi, M. I., Iftikhar, M., Janjua, S. Y., Zaman, K., Raja, U. M., & Javed, Y. (2015). Empirical investigation of mobbing, stress and employees' behavior at work place: quantitatively refining a qualitative model. *Quality & Quantity*, *49*, 93-113.

Tınaz, P. (2011). İşyerinde psikolojik taciz (mobbing). *Beta Publishing, Istanbul, Türkiye.*

Tınaz, P., Bayram, F., & Ergin, H. (2008). Çalışma Psikolojisi ve Hukuki Boyutlarıyla İşyerinde Psikolojik Taciz (Mobbing). *Beta Publishing, Istanbul, Türkiye.*

Tigrel, E. Y., & Kokalan, O. (2009). Academic mobbing in Turkey. *International Journal of Educational and Pedagogical Sciences*, *3*(7), 1473-1481.

Wahyudi Rahman, M. F., Partiwi, S. G., & Widyaningrum, R. (2024). Psychosocial Factors Issues in Construction Workers: A Systematic Review and Future Research Directions. International Journal of Safety & Security Engineering, 14(1).

Yavuz H., (2007). *Çalışanlarda mobbing (psikolojik şiddet) algısını etkileyen faktörler: SDÜ Tıp Fakültesi üzerine bir araştırma* [Master's thesis]. Süleyman Demirel University, Isparta, Türkiye.

Yokouchi, N., Ambe, T., Fujisaki-Sueda-Sakai, M., & Ozawa, K. (2024). Workplace bullying and harassment in the Japanese construction industry: prevalence and associations with subjective health and work attractiveness. *Construction Management and Economics*, 1-17.

Social Life Cycle Assessment in the Turkish Construction Industry: A Survey Study

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Abstract

The construction industry, with high resource consumption and waste production, requires a life cycle analysis considering environmental, economic, and social factors for sustainable development. The sector's multi-stakeholder structure affects numerous individuals, making it crucial to analyze its social and socio-economics impacts. A social life cycle assessment was conducted to identify the social and socio-economic aspects of various stakeholders which are selected as worker, employer, society in the Turkish construction industry through a survey. S-LCA awareness in the Turkish construction industry was found to be 28.5%, based on the findings of a survey in which 109 stakeholders participated. Employers consider themselves to have faced discrimination in accessing opportunities that provide equal opportunities, such as state support. It was concluded that worker performance in the construction industry will increase if the social issues of freedom of association, collective bargaining, training and education are improved. The only social indicator that society stakeholder appears to be pleased with is local employment.

Keywords: *construction industry, social impact, social life-cycle assessment, S-LCA.*

Introduction

The construction sector is one of the major industries for employment and economic development but its responsible for high consumption rate of natural sources and high waste production. Life cycle assessment (LCA) in construction sector is adopted for these environmental concerns. However, the industry also suffers by social problems including unemployment and workplace accidents (Ayassamy & Pellerin, 2023).

Due to periodic employment of construction sector, workers face most likely high poverty and unemployment rates (Candaş, 2010). According to 2022 statistics data, Turkey is comprising over 210 thousand construction establishments and encompassing approximately 1.8 million construction employees. Furthermore, the statistical institute reports over 64 thousand construction occupational accidents, with 422 fatalities (CSGB, 2022).

The construction sector, with its highly multi-stakeholder structure, directly or indirectly affects numerous individuals both internal and external of its scope. Therefore, when the life cycle assessment of the construction sector, it is necessary to analyze its social impacts. Additionally, identifying current and potential social impacts will facilitate decision-making processes.

This study aims to evaluate the social and socio-economic aspects of various stakeholders (workers, employers, and society) in the construction sector, encompassing existing and potential positive and negative impacts throughout their life cycle.

An Overview of LCA and S-LCA

Life cycle assessments were initially considered from an environmental perspective. Therefore, when LCA is mentioned, a technique that examines the environmental aspects and potential environmental impacts of a product or service throughout its life cycle assessments comes to mind (UNEP, 2009). However, recently the scope of life cycle assessment has been expanded. Assessments of life cycle now also include economic and social impacts (Hossain et al., 2018).

There are several life cycle models or variants of LCA such as cradle-to-grave, cradle-to-gate, and gate-to-gate or gate-to-grave (UNEP, 2009). In literature, different variants of LCA have been found such as cradle-to-end of construction (Dong & Ng, 2015). The building industry in Europe is governed by the EN 15804 (CEN, 2020) and EN 15978 (CEN, 2012) standards, which include the various stages of the building life cycle. Furthermore, ISO 14040 (2020) provide details on life cycle assessment (LCA), including phases and variants.

Social Life Cycle Assessment (S-LCA) is a method used to analyze the social and socio-economic impacts of a product or service throughout its life cycle (UNEP, 2009). Social and socio-economic impacts are factors that can directly affect stakeholders positively or negatively. Thus, S-LCA is a methodology that supports decision-making to improve social conditions in life cycles and value chains (UNEP, 2020). The first guideline related to S-LCA was published in 2009 by United Nations Environment Programme (UNEP) and Society of Environmental Toxicology and Chemistry (SETAC) (UNEP, 2022).

S-LCA examines social and socio-economic impacts on stakeholders. According to UNEP (2009), 5 stakeholders are identified: Workers; Local community; Society; Consumers; and Value chain actors. Stakeholder categories include impact subcategories with socially significant themes, such as worker rights, child labor, fair salary, working hours, etc. Various indicators can be used to evaluate each subcategory, depending on the context of the study (Hossain et al., 2018; UNEP, 2020).

Literature Review

LCA implements in the literature have been observed in a wide range of industries, such as agriculture (Goglio et al., 2018), construction (Zheng et al., 2019), transportation (Bilgili et al., 2019), mining (Suppen et al., 2006), and manufacturing (KEK & S, 2016). LCA has been applied through case studies in the construction industry, especially in terms of investigating environmental impacts (Vitorio Junior & Kripka, 2020). Searches across a number of academic search engines revealed that there were significantly less publications on S-LCA than there were on LCA.

Wu et al. (2014) conducted a literature review for S-LCA and summarized in terms of goal, coverage, approach, data, indicator and methods, as shown in Figure 1. Vavra et al. (2021) researched the factors affecting the motivation of employees in a selected medium-sized company. Liu et al. (2018) conducted research on the human health assessment of construction sector stakeholders.

Even though there are few publications about S-LCA in construction industry, it was applied to several types of construction in countries like China, Brazil, Malaysia, Germany, Singapore, and more. Dong and Ng (2015) developed S-LCA model for evaluating social impacts to adopt precast concrete elements in Hong Kong construction industry. According to results, using precast elements could have a negative effect on local employment and fair salaries. Balasbaneh et al. (2018) selected five types of hybrid timber building construction in Malaysia to analyze the economic contribution of the stakeholders for S-LCA and findings indicated that the timber industry will provide workers higher salaries and more job opportunities.

The number of S-LCA studies carried out about Türkiye construction industry has been found is quite restricted. Cici et al. (2022) conducted a study in which they compared the social impacts of blue and white-collar employees working in cement production processes, covering the social life cycle.

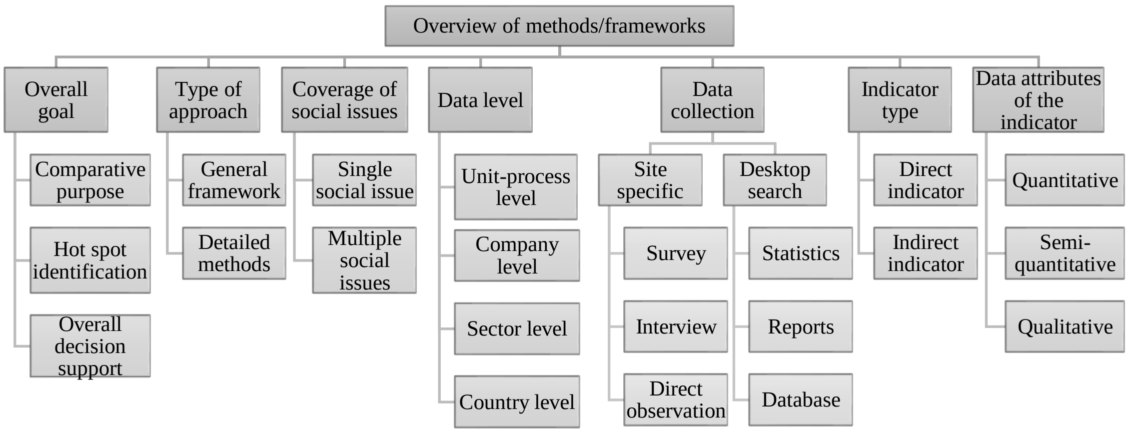

Figure 1: Overview of the classification of S-LCA methodologies (Wu et al., 2014).

Materials and Methods

S-LCA method which used in this study consists of four iterative stages: Goal and Scope Definition, Inventory Analysis, Impact Assessment, and Interpretation (Ayassamy & Pellerin, 2023; UNEP, 2020).

To determine *the goal and scope* of the study is the first of the S-LCA's four phases (UNEP, 2009). It is important to decide functional units, system boundary and social indicators in goal and scope definition. System boundary identifies the parts of the system or product being evaluated and the geographical constraints of the system. Social conditions differ from diverse local area and diverse parts of life cycle (İlhan, 2018). The goal of this study is to assess the current and potential positive and negative impacts of social and socio-economic factors on various stakeholders in the Turkish construction sector in terms of the life cycle of structure — the construction phase only. The scope of this study is determined according to EN 15804 and EN 15978 standards as “construction process stage (A4-5 modules)” in building life cycle. This S-LCA survey study covers gate-to-end of construction.

9 subcategories in the employee stakeholder category, 7 in the employer stakeholder category, and 4 in the society stakeholder category were selected from UNEP guideline according to suitability for this study. The functional unit was not specified since it is a general survey, and the use of functional units in S-LCA is also an issue of dispute (Hossain et al., 2018).

During *the inventory analysis* phase, the questions determined in the subcategories were collected through an online survey to the relevant stakeholders. The survey includes 13 yes/no questions and 17 five-point Likert scale questions for employees, 12 yes/no questions and 5 five-point Likert scale questions for employers, and 5 yes/no questions and 5 five-point Likert scale questions for society.

Information about how to calculate findings for *impact assessments* is derived from pilot projects on guidelines provided by (UNEP, 2022). A default score between 1 and 5 has been determined, varying on whether the social impact of the question is positive or negative. If yes/no question has a negative social impact and answer is yes than default score will be 1. The score for each answer in a question is obtained by multiplying the percentage of each answer by its default score. The grand score of the question is found by the sum of the scores of each answer to that question. The subcategory score is obtained by averaging the grand scores of the questions in each subcategory. These scores do not mean anything without a performance scale. The performance scale used in this study is given in Figure 2.

2 Excellent	1 Above Satisfactory	0 Satisfactory	-1 Slightly Below Satisfactory	-2 Unsatisfactory / Requires Improvement
4.1-5.0	3.26-4.0	2.76-3.25	2.1-2.75	1.0-2.0

Figure 2: Performance scale.

In the *interpretation phase*, which is the last step of the S-LCA study, the results of the findings obtained in the previous two stages were explicated.

Results

An online survey consisting of two sections was created for this study. An initial question at the very beginning of survey was made to the participants to figure out their awareness with social life cycle assessment. Then, demographic questions such as gender, age, and education level were asked, and the participant's stakeholder category was asked at the end of the first section. Since the social impact questions are different for each stakeholder category, the second part of the survey includes the questions of the selected stakeholder category.

As a result, 109 participants in all, 69% men and 31% women, took part in the survey. 62% of the participants are between the ages of 18-30 and 22% are between the ages of 31-40. The number of participants over the age of 40 is only 17. Among the participants, 56% have a bachelor's degree, 28% have a postgraduate degree, 12 participants have an associate degree, and 4 participants for each are primary and high school graduates. Merely 28.5% of the total participants hold a point of view on S-LCA. 63 workers, 18 employer and 28 society participated to survey.

Workers have been posed questions about subcategories. In Table 1, the evaluation results of the social performance of the construction industry in Türkiye are given according to the responses of the participants in the worker stakeholder to the survey. Participants in the worker stakeholder group stated that they found satisfactory the social performance of the construction industry in the *working hours, forced labor, and equal opportunities* subcategories. However, in the working hours subcategory, working more than 45 hours was found to be slightly below the performance satisfactory level. They estimated the social performance of the construction sector as quite satisfactory in the subcategories of *child labor, fair salary, health and safety, and social security*. Although the result was satisfactory in the fair salary subcategory, worker stakeholders also stated that their salaries were not enough for social activities. In the subcategories of *freedom of association/collective bargaining and training/ education*, they stated that the social performance was slightly below satisfactory level.

Table 1. Social performance of the worker stakeholder.

Stakeholder	**Sub-Categories**	**No. of Indicators**	**Score**	**Performance Scale**
WORKER	Freedom of Association/ Collective Bargaining	3	2.71	-1
	Child Labor	1	3.46	+1
	Fair Salary	4	3.36	+1
	Working Hours	4	2.78	0
	Forced Labor	4	2.81	0
	Equal Opportunities / Discrimination	5	2.92	0
	Health and Safety	5	3.30	+1
	Training and Education	2	2.59	-1
	Social Security	2	3.29	+1

Table 2. Social performance of the employer stakeholder.

Stakeholder	**Sub-Categories**	**No. of Indicators**	**Score**	**Performance Scale**
EMPLOYER	Freedom of Association/ Collective Bargaining	2	2.33	-1
	Child Labor	1	4.56	+2
	Fair Salary	3	3.06	0
	Working Hours	2	2.79	0
	Construction Costs	2	2.69	-1
	Equal Opportunities / Discrimination	2	2.03	-1
	Worker Quality	3	3.31	+1
	Social Benefits	2	3.67	+1

Employers have been posed questions about as subcategories. In Table 2, the evaluation results of the social performance of the construction industry in Türkiye are given according to the responses of the participants in the employer stakeholder to the survey. Participants in the employer stakeholder stated that they found the social performance of the construction industry satisfactory in the *working hours and fair salary* subcategories. However, when compared with the salaries offered to the workers of other companies in the Turkish construction sector, it was seen that the salaries they offered were slightly below the satisfactory level. Employer participants who stated that they had never employed child labor gave very high scores to the social performance of the construction sector in the *child labor* subcategory. In the *worker quality and social benefits* subcategories, they evaluated the social performance of the construction sector as quite satisfactory. In the *freedom of association/collective bargaining, construction costs, and equal opportunities* subcategory, they stated that the social performance was significantly lower than the satisfactory level.

Table 3. Social performance of the society stakeholder.

Stakeholder	**Sub-Categories**	**No. of Indicators**	**Score**	**Performance Scale**
SOCIETY	Community Engagement	5	2.45	-1
	Cultural Heritage	1	2.43	-1
	Safe/Healthy Living Conditions	3	2.14	-1
	Local Employment	1	3.29	+1

Society have been posed questions regarding the society participation, cultural heritage, safe living conditions and local employment as subcategories. In Table 3, the evaluation results of the social performance of the construction industry in Türkiye are given according to the responses of the participants in the society stakeholder to the survey. Participants in the society stakeholder stated that they found the social performance of the construction industry quite low in the subcategories of *community engagement, cultural heritage, and safe/healthy living conditions.* In the *local employment* subcategory, they stated that the social performance was higher than satisfactory.

Conclusions

This social life cycle assessment was conducted to identify the social and socio-economic aspects of various stakeholders in the Turkish construction industry, encompassing existing and potential positive and negative impacts throughout their life cycle. For this purpose, the stakeholders, which are workers, employers, society, that most affect the Turkish construction industry were determined and a survey was conducted to analyze the social impacts of these stakeholders. The stakeholders that have the most impact on the Turkish construction industry were chosen as employers, workers, and society. Social factors that have the major impact on these stakeholders, such as fair salary, working hours, equal opportunities/ discrimination, health and safety, were used in the analysis.

According to the survey findings, it was concluded that worker performance in the construction industry will increase if the social issues of freedom of association, collective bargaining, training and education are improved. Construction costs have increased considerably in the

Turkish construction industry due to increasing inflation and exchange rates. This social impact is also reflected in the survey results for employers. In addition, employers feel discrimination in accessing opportunities that provide equal opportunities, such as state supports. With the improvements made in construction costs and equal opportunities/discrimination, the Turkish construction sector can be revived and support economic development. The only social indicator that society appears to be pleased with is local employment, according to survey.

There are remarkably few studies in our country involving social life cycle assessments. In addition to improving social performance, it is believed that the study's findings will offer decision-makers new perspectives on all the benefits and drawbacks of social and socioeconomic factors in the construction industry. They will also serve as a point of reference for further research.

References

Ayassamy, P., & Pellerin, R. (2023). Social life-cycle assessment in the construction industry: A review of characteristics, limitations, and challenges of S-LCA through case studies. *Sustainability (Switzerland)*, *15*(19). https://doi.org/10.3390/su151914569

Balasbaneh, A. T., Marsono, A. K. B., & Khaleghi, S. J. (2018). Sustainability choice of different hybrid timber structure for low medium cost single-story residential building: Environmental, economic and social assessment. *Journal of Building Engineering*, *20*, 235–247. https://doi.org/10.1016/j.jobe.2018.07.006

Bilgili, L., Kuzu, S. L., Çetinkaya, A. Y., & Kumar, P. (2019). Evaluation of railway versus highway emissions using LCA approach between the two cities of Middle Anatolia. *Sustainable Cities and Society*, *49*, 101635. https://doi.org/10.1016/j.scs.2019.101635

Candaş, A. (2010). *Türkiye'de Eşitsizlikler: Kalıcı Eşitsizliklere Genel Bir Bakış*. https://spf.bogazici.edu.tr/sites/spf.boun.edu.tr/files/1439796553_turkiyede_esitsizlikler_spf_0.pdf

CEN. (2012). *EN 15978 Sustainability assessment of construction works – assessment of environmental performance of buildings – calculation method*.

CEN. (2020). *EN 15804:2012+A2:2020 Sustainability of construction works - environmental product declaration - core rules for the product category of construction product*.

Cici, B., Pekey, B., & Çankaya, S. (2022). Üretim sektöründe sürdürülebilirlik için sosyal yaşam döngüsü değerlendirmesi: Çimento üretimi örneği. *Journal of Advanced Research in Natural and Applied Sciences*, *8*(4), 651–661.

CSGB. (2022). *İnşaat Sektörü SGK İstatistikleri 2022*. https://guvenliinsaat.csgb.gov.tr/media/ydlhom2c/in%C5%9Faat-sekt%C3%B6r%C3%BC-2022-istatistikleri.pdf

Dong, Y. H., & Ng, S. T. (2015a). A social life cycle assessment model for building construction in Hong Kong. *International Journal of Life Cycle Assessment*, *20*(8), 1166–1180. https://doi.org/10.1007/s11367-015-0908-5

Goglio, P., Brankatschk, G., Knudsen, M. T., Williams, A. G., & Nemecek, T. (2018). Addressing crop interactions within cropping systems in LCA. *The International Journal of Life Cycle Assessment*, *23*(9), 1735–1743. https://doi.org/10.1007/s11367-017-1393-9

Hossain, M. U., Poon, C. S., Dong, Y. H., Lo, I. M. C., & Cheng, J. C. P. (2018). Development of social sustainability assessment method and a comparative case study on assessing recycled construction materials. *International Journal of Life Cycle Assessment*, *23*(8), 1654–1674. https://doi.org/10.1007/s11367-017-1373-0

İlhan, B. (2018). *A life cycle sustainability assessment methodology for thermal insulation materials* [The degree of Master of Science]. Middle East Technical University.

ISO 14040. (2020). *Environmental Management – Life Cycle Assessment – Principles and Framework*.

KEK, V., & S, V. (2016). LCA integrated ANP framework for selection of sustainable manufacturing processes. *Environmental Modeling & Assessment*, *21*(4), 507–516. https://doi.org/10.1007/s10666-015-9490-2

Liu, R., Gong, Z., & Nui, J. (2018). A human health assessment in construction industry from S-LCA perspective. *6th International Symposium on Project Management (ISPM)*, 86–92.

Suppen, N., Carranza, M., Huerta, M., & Hernández, M. A. (2006). Environmental management and life cycle approaches in the Mexican mining industry. *Journal of Cleaner Production*, *14*(12–13), 1101–1115. https://doi.org/10.1016/j.jclepro.2004.12.020

UNEP. (2009). Guidelines for Social Life Cycle Assessment of Products. *Environment*.

UNEP. (2020). Guidelines for social life cycle assessment of products and organizations. United Nations environment programme. *United Nations environment programme (Unepe)*, *2*, 1–140.

UNEP. (2022). *Pilot projects on guidelines for social life cycle assessment of products and organizations 2022*.

Vavra, J., Patak, M., Kostalova, J., & Bednarikova, M. (2021). S-LCA indicators as employee motivation factors. *European Journal of Sustainable Development*, *10*(2), 267. https://doi.org/10.14207/ejsd.2021.v10n2p267

Vitorio Junior, P. C., & Kripka, M. (2020). Fair wage potential as a tool for social assessment in building projects. *Engineering, Construction and Architectural Management*, *28*(4), 1295–1318. https://doi.org/10.1108/ECAM-01-2020-0024

Wu, R., Yang, D., & Chen, J. (2014). Social life cycle assessment revisited. *Sustainability (Switzerland)*, *6*(7), 4200–4226). https://doi.org/10.3390/su6074200

Zheng, X., Easa, S. M., Yang, Z., Ji, T., & Jiang, Z. (2019). Life-cycle sustainability assessment of pavement maintenance alternatives: Methodology and case study. *Journal of Cleaner Production*, *213*, 659–672. https://doi.org/10.1016/j.jclepro.2018.12.227

Re-evaluating Modular Construction through the Lens of Circularity

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Abstract

Modular construction and circular economy are two concepts that are gaining momentum in the construction industry. Modular construction minimizes waste and reduces the need for new materials. It makes it easier to disassemble structures and reuse them at the end of their useful life. At this point, the research investigates the intersection of modular construction and circularity, redefining traditional processes in the built environment. With an increasing emphasis on sustainable practices, circular economy principles are integrated into the modular construction process, challenging the linear 'take-make-dispose' model. This study aimed to examine the impact of modular construction on waste management and sustainability by focusing on the potential of reusing modular buildings. The research indicates that modularity with circularity can promote maximizing the building module's life span and reusing them. However, there is a need for large-scale adoption of circular economy to achieve the goal of near-zero waste in modular construction because the current work in the field is still fragmented and immature.

Keywords: *circular economy, design for disassembly, modular construction, waste management.*

Introduction

The construction industry consumes up to 50% of natural resources and is responsible for 40% of the world’s energy consumption, 30% of raw material utilization, 25% of water use, and 33 % of global CO_2 emissions (Ajayi et al., 2015; Calle Müller et al., 2024). Moreover, the construction industry contributes the largest portion of waste to landfills (Ajayi et al., 2016; O’Grady et al., 2021), generating 35% of waste to landfills across the globe (Solís-Guzmán et al, 2009). The UK construction industry accounts for 44% of landfill waste, compared to 44% in Australia and 29% in the US (Ajayi et al., 2016). At this point, waste from construction and demolition (C&D) activities remains a concern. According to the UK Building Record Establishment (BRE, 2003) guide, reducing waste by 5% could save the UK construction industry up to £130 million. This evidence illustrates the economic advantage of reducing waste in addition to environmental benefits (Ajayi et al., 2015).

The construction industry is traditionally based on the ‘take-make-dispose of’ model (Mangialardo & Micelli, 2018). The flow of the generic phases of a typical construction project depicted by Eastman (2011) ends with the planning considered ‘as demolished’. Buildings eventually end up in landfills, causing a significant loss of valuable metals, minerals, and organic materials to future generations (Jayasinghe & Waldmann, 2020). During the life cycle of an asset, waste is generated, but the end-of-life phase is the least sustainable phase, considering the amount of waste generated by the demolition process (Charef et al., 2021). In the building industry, waste can be produced in the construction phase owing to design errors, on-site mistakes, unpredicted items of work, renovation, etc. (Akbarieh et al., 2020). Nevertheless, a major proportion of the waste belongs to the demolition phase of the buildings at the end of their life (Vefago & Avellaneda, 2013). The demolition phase is responsible for 50% of all waste generated by the AEC sector worldwide (Kibert, 2016). Currently, all over the world, construction and demolition waste production is monitored proving that the problem has been recognized (Cai et al., 2019). Environmental pressures (finite natural resources, generation skill shift, and exponential technology growth) and regime pressures (linear supply chain, one-off mentality, etc.) will force significant changes in practices in the construction industry (Ferng, 2021). At this point, modularity could be a key point for avoiding demolition and reducing waste to zero of buildings by simplifying the process of disassembling at the end of the first building’s life cycle (Ferreira et al., 2020). It is claimed that modular technology can reduce construction waste up to 84.7% and also, construction projects' waste output could be reduced by 52% by identifying and using prefabrication system (Ajayi et al., 2017; Yuan et al., 2022). Moreover, modular buildings with the integration of Circular Economy (CE) are thought as a potential sustainable construction process (Zairul, 2021).

The CE represents a way to overcome the contradiction between economic growth and environmental sustainability. CE has attracted interest in the practice of sustainability by moving away from the current linear business model (take, make, use, and dispose) to a circular business model (reduce, reuse, recycle, and recover) (Eberhardt et al., 2019). In light of this, to reduce the environmental impacts of waste and to contribute to economic growth, the transition to a CE strategy is considered a solution (Ruiz et al., 2020). Therefore, construction and demolition waste management are of increasing interest to academic researchers, who seek to shift the sector into a new paradigm with the advent of the CE (Geissdoerfer et al., 2017; Charef et al., 2021). In a CE approach, the reuse of components will be possible primarily by design for disassembly (Akinade et al., 2015). Despite the lack of marketability of reuse, design for disassembly and reuse has been gaining attention through modular building technology (Minunno et al., 2020). Modularity with the circular economy in the built environment changes the architectural perspective and construction from a permanent to a mutable building, from a linear to a circular process (Ferreira et al., 2020).

Background and Research Significance

The concepts of 'reusability, reversibility, regeneration, and reassembly' are still not widely adopted in the construction sector. Typically, the management of buildings' life cycles concludes with demolition, but this should not be the end of the process. The industry often overlooks 'design for disassembly' during the design phase, leading to economic and environmental damage from demolition waste. To truly achieve a circular approach, the construction industry must consider end-of-life treatment of buildings in waste management strategies. Geissdoerfer et al. (2017) characterize the circular economy as a regenerative closed-loop system that can be realized through suitable design, maintenance, refurbishment, or reuse practices. This definition aligns effectively with modular relocatable buildings. Moreover, commercial entities often delineate essential elements of the circular economy, encompassing resource efficiency, the preservation and extension of existing resources, forward-looking design, reconsideration of business models, collaboration, and leveraging technology and digitalization (Circle Economy, 2017). Many of these elements are inherent in modular building solutions (Kyrö et al., 2019). Modular construction is increasingly viewed as the path forward to enhance the industry's competitiveness, as it offers significant advantages over traditional construction methods.

In contrast to the commonly held belief, modular construction is not a recent technological innovation. It emerged in the late 1800s with the Industrial Revolution and the introduction of machinery, leading to the adoption of prefabrication techniques in factory settings. While not much has evolved since then, prefabrication/modularization has recently gained significant attention in the construction sector, often described as a contemporary construction approach. What has sparked this renewed interest? Why is it happening now? And what lies ahead?

In light of these questions, this study aims to re-discover the potential of modular construction with a circular economy approach. The research objectives are to search the applicability of CE principles to modular buildings and to take an attention to reuse instead of recycling in modular buildings that could deliver circularity. The objectives are reached through a literature review.

Circular Economy (CE) Approach in Modular Construction

Circular economy (CE) is an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling, and recovering materials in production/distribution and consumption processes (Ghaffar et al., 2020). CE concept provides the usage of renewable energy in production systems, the adoption of innovative business models which catalyze collaboration and technological innovation, and the improvements in performance and efficiency of products in which wastes are eliminated from supply chains (Antwi-Afari et al., 2021). CE is considered an innovative practice to foster sustainability in a systematic way and move away from the basic linear economy model, which consists of "extract, use, and landfill". It encourages the reduction of raw materials inputs, relies on renewable sources, and eliminates waste from the system (Rahla et al., 2021). Since 2018, the rise of the "circular economy" signifies one of the new guiding principles for the construction industry (Wang et al., 2023).

CE, defined as a regenerative closed loop system, which can be achieved, through appropriate design, maintenance, refurbishing, or reuse, fits modular relocatable buildings well (Kyrö et al., 2019). The effort to apply CE principles in conventional buildings represents a monolithic effort in nature (Minunno et al., 2018). The way modular buildings are designed and assembled facilitates improved disassembly, reuse, and circular flow of resources (Benjamin et al., 2022). Therefore, prefabrication and modular technology are the ideal solutions for waste reduction and a lean supply chain in the construction industry (Zairul, 2021). End-of-life recycling and reuse of construction components and units are considered good environmental practices. Recycling and reusing can offer great potential for improving and enhancing resource efficiency in the construction sector, providing reductions in energy use and associated carbon emissions, reducing the amount of waste and land put out of use, and creating value (Union, 2014; Iacovidou et al., 2016). Reuse is the process during which discarded components are recirculated (and sometimes upgraded according to the material structure) and used for the same function without destruction (Cooper & Allwood, 2012) while recycling is the process by which discarded materials are reprocessed into raw materials for new products (Thormark, 2000). A study conducted by Minuno et al. (2020) compared the life cycle assessment (LCA) of a circular building, designed for disassembly and reuse, against its conventional (linear) modular building, which lacks disassembly design and disposes of materials through recycling or landfill. The results showed that the environmental advantages of reuse methods may significantly outweigh those of recycling. To justify this, the environmental advantages of a prototype modular building specifically designed for disassembly and reuse by conducting a life cycle assessment of its components are assessed. The findings suggest that designing and constructing components for reuse instead of recycling reduces greenhouse gas emissions by 88% and positively impacts various other environmental indicators evaluated in the study seen in Figure 1 (Minuno et al., 2020).

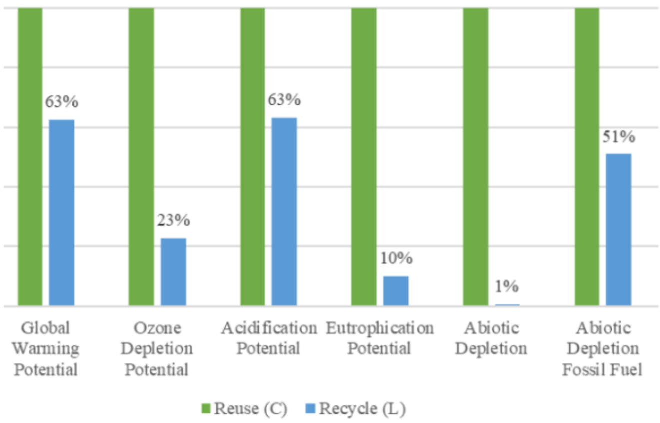

Figure 1: Environmental impacts of reusing vs recycling practices (Minuno et al., 2020).

A more financially and ecologically advantageous approach to using reclaimed building materials involves directly reusing materials and components, which consumes minimal energy compared to the energy and resources required for material recycling. Figure 2 indicates that the most significant economic and environmental benefits within the built environment can be attained through a high level of material recoverability via methods such as Design for Disassembly (DfD). Reusing entire buildings is thought to offer the greatest economic and environmental advantages, even though they are frequently not designed with this intention (Eberhardt et al., 2019).

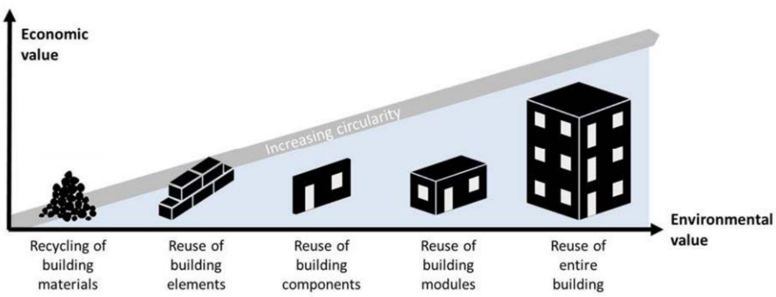

Figure 2: Interpretation of the level of circularity in terms of both economic and environmental values (Eberhardt et al., 2019).

As a synthesis of this information, "designing for disassembly" stands out as a significant strategy for implementing CE principles in modular construction (Jayawardana et al., 2023). Modular buildings can be swiftly delivered as pre-assembled modules, minimizing disruption at the site. Standardized solutions provide versatility and superior quality, ensuring excellent indoor comfort and access to daylight and views for occupants. Due to the leasing model and the temporary nature of modular buildings, they offer flexibility without the ownership burden and can be situated within existing urban infrastructure or on-site. Additionally, modular buildings exhibit high adaptability, allowing modules to be added or removed according to evolving space requirements. These attributes enhance usability, circularity, or both. Importantly, certain features stemming from the leasing model, like the ability to add or remove modules and integrate them into the existing urban environment or on-site, contribute to the usability of modular buildings. Likewise, the multi-functionality offered by standard modular solutions promotes circularity (Kyrö et al., 2019).

In the current condition, the extraction and reutilization of prefabricated components are not actively encouraged to ensure resource efficiency downstream of the construction system. According to Iacovidou et al. (2021), this is attributed to two main factors: firstly, the prevalent linear management approach to construction resources, which places little emphasis on recovery at the end of the building's service life; and secondly, the lack of confidence in the quality and remaining functionality of structural modular components, which necessitates significant investments of both time and money for quality control. Furthermore, obstacles to reuse may include building codes and standards, uncertainties regarding the structural properties and performance of reused components, technical constraints, and the absence of end markets for secondary materials, as well as biases and a lack of awareness regarding the potential benefits of this practice (Iacovidou et al., 2016). In existing literature, only a limited number of studies address prefabricated reusable building modules. Aye et al. (2012) found that reusing even a small portion (by volume) of embodied energy at the end of a building's useful life can lead to significant savings in embodied energy for both concrete and prefabricated steel and timber systems. Their findings demonstrated that incorporating existing materials into a new building can save up to 81.3% of embodied energy for prefabricated steel buildings, up to 69.1% for prefabricated timber buildings, and up to 32.3% for concrete buildings. This study clearly highlights the potential of prefabricated construction to offer enhanced environmental performance compared to conventional methods, provided they are initially designed for reuse, either adaptively or through disassembly.

Discussion and Conclusion

Modular construction, a developing building technique, possesses characteristics that contribute to the circularity of materials, building components, and the building itself. Integrating the CE concept into modular construction will facilitate informed decision-making during the initial stages of modular building projects. CE-driven modular construction especially fosters the 'design for disassembly' strategy. Decisions regarding the fate of the building's deconstruction, such as whether to reuse the entire building, reuse components in other buildings, or recycle materials, are crucial aspects of design-for-disassembly. The reviewed literature highlighted that reusing the buildings contributes to all levels of circularity. Therefore, the industry will focus on the relocatable modular buildings that could deliver reusability and circularity in recent times. Relocatable modular buildings have the potential to address the issues arising from rapidly changing demographics across various regions while offering both usability and circularity. These buildings utilize existing urban structures and infrastructure and are also resource-efficient to produce, thanks to factory prefabrication. Moreover, the design-for-disassembly version of the modular units, in other words, relocatable modular buildings performs better in terms of all environmental impacts compared to recycling practices or reusing components. This shows the importance of going for design-for-disassembly-driven CE strategies at the design stage of a modular building. In this context, modular construction with the adoption of CE is designed to be manipulated, added, and maintained during its lifecycle, aiming to be reconfigured, relocated, or disassembled for reuse without generating waste.

References

Ajayi, S. O., Oyedele, L. O., Bilal, M., Akinade, O. O., Alaka, H. A., Owolabi, H. A., & Kadiri, K. O. (2015). Waste effectiveness of the construction industry: understanding the impediments and requisites for improvements. *Resources, Conservation and Recycling, 102*, 101-112.

Ajayi, S. O., Oyedele, L. O., Akinade, O. O., Bilal, M., Owolabi, H. A., Alaka, H. A., & Kadiri, K. O. (2016). Reducing waste to landfill: a need for cultural change in the UK construction industry. *Journal of Building Engineering*, *5*, 185-193.

Ajayi, S. O., Oyedele, L. O., Akinade, O. O., Bilal, M., Alaka, H. A., Owolabi, H. A., & Kadiri, K. O. (2017). Attributes of design for construction waste minimization: a case study of waste-to-energy project. *Renewable and Sustainable Energy Reviews*, *73*, 1333-1341.

Akbarieh, A., Jayasinghe, L. B., Waldmann, D., & Teferle, F. N. (2020). BIM-based end-of-lifecycle decision making and digital deconstruction: Literature review. *Sustainability*, *12*(7), 2670.

Akinade, O. O., Oyedele, L. O., Bilal, M., Ajayi, S. O., Owolabi, H. A., Alaka, H. A., & Bello, S. A. (2015). Waste minimisation through deconstruction: A BIM based Deconstructability Assessment Score (BIM-DAS). *Resources, Conservation and Recycling, 105*, 167-176.

Antwi-Afari, P., Ng, S. T., & Hossain, M. U. (2021). A review of the circularity gap in the construction industry through scientometric analysis. *Journal of Cleaner Production, 298*, 126870.

Aye, L., Ngo, T., Crawford, R. H., Gammampila, R., & Mendis, P. (2012). Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules. *Energy and Buildings*, *47*, 159-168.

Benjamin, S., Christopher, R., & Carl, H. (2022). Feature modeling for configurable and adaptable modular buildings. *Advanced Engineering Informatics*, *51*, 101514.

Bertram, N., Fuchs, S., Mischke, J., Palter, R., Strube, G., & Woetzel, J. (2019). Modular construction: from projects to products. *McKinsey & Company: Capital Projects & Infrastructure*, *1*, 1-34.

BRE (2003). *Construction and demolition waste: good buildings guide 57 part 1*. Building Research Establishment.

Cai, G., & Waldmann, D. (2019). A material and component bank to facilitate material recycling and component reuse for a sustainable construction: concept and preliminary study. *Clean Technologies and Environmental Policy*, *21*, 2015-2032.

Calle Müller, C., Pradhananga, P., & ElZomor, M. (2024). Pathways to decarbonization, circular construction, and sustainability in the built environment. *International Journal of Sustainability in Higher Education*.

Charef, R., Morel, J. C., & Rakhshan, K. (2021). Barriers to implementing the circular economy in the construction industry: a critical review. *Sustainability*, *13*(23), 12989.

Circular Economy (2017). *Making sense of the circular economy–the 7 key elements*. www.circle-economy.com/the-7-key-elements-of-the-circular-economy

Cooper, D. R., & Allwood, J. M. (2012). Reusing steel and aluminium components at end of product life. *Environmental Science & Technology*, *46*(18), 10334-10340.

Eastman, C. M., Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2011). *BIM handbook: a guide to building information modeling for owners, managers, designers, engineers and contractors*. John Wiley & Sons.

Eberhardt, L. C. M., Birgisdottir, H., & Birkved, M. (2019). Potential of circular economy in sustainable buildings. *IOP Conference Series: Materials Science and Engineering*, *471*, 092051.

Ferng, J. (2021). Construction. *CTBUH Journal*, *2*, 46-53.

Ferreira Silva, M., Jayasinghe, L. B., Waldmann, D., & Hertweck, F. (2020). Recyclable architecture: prefabricated and recyclable typologies. *Sustainability*, *12*(4), 1342.

Ghaffar, S. H., Burman, M., & Braimah, N. (2020). Pathways to circular construction: an integrated management of construction and demolition waste for resource recovery. *Journal of Cleaner Production*, *244*, 118710.

Geissdoerfer, M., Savaget, P., Bocken, N. M., & Hultink, E. J. (2017). The circular economy–a new sustainability paradigm? *Journal of Cleaner Production*, *143*, 757-768.

Jayasinghe, L. B., & Waldmann, D. (2020). Development of a BIM-based web tool as a material and component bank for a sustainable construction industry. *Sustainability*, *12*(5), 1766.

Jayawardana, J., Sandanayake, M., Kulatunga, A. K., Jayasinghe, J. A. S. C., Zhang, G., & Osadith, S. U. (2023). Evaluating the circular economy potential of modular construction in developing economies—a life cycle assessment. *Sustainability*, *15*(23), 16336.

Iacovidou, E., & Purnell, P. (2016). Mining the physical infrastructure: opportunities, barriers and interventions in promoting structural components reuse. *Science of the Total Environment*, *557*, 791-807.

Kibert, C. J. (2016). *Sustainable construction: green building design and delivery*. John Wiley & Sons.

Kyrö, R., Jylhä, T., & Peltokorpi, A. (2019). Embodying circularity through usable relocatable modular buildings. *Facilities*, *37*(1/2), 75-90.

Mangialardo, A., & Micelli, E. (2018). Rethinking the construction industry under the circular economy: principles and case studies. *Smart and Sustainable Planning for Cities and Regions: Results of SSPCR 2017 2,* pp. 333-344.

Minunno, R., O'Grady, T., Morrison, G. M., & Gruner, R. L. (2020). Exploring environmental benefits of reuse and recycle practices: a circular economy case study of a modular building. *Resources, Conservation and Recycling*, *160*, 104855.

O'Grady, T. M., Minunno, R., Chong, H. Y., & Morrison, G. M. (2021). Interconnections: an analysis of disassemblable building connection systems towards a circular economy. *Buildings*, *11*(11), 535.

Rahla, K. M., Mateus, R., & Bragança, L. (2021). Implementing circular economy strategies in buildings—from theory to practice. *Applied System Innovation*, *4*(2), 26.

Ruiz, L. A. L., Ramón, X. R., & Domingo, S. G. (2020). The circular economy in the construction and demolition waste sector–a review and an integrative model approach. *Journal of Cleaner Production*, *248*, 119238.

Solís-Guzmán, J., Marrero, M., Montes-Delgado, M. V., & Ramírez-de-Arellano, A. (2009). A Spanish model for quantification and management of construction waste. *Waste Management*, *29*(9), 2542-2548.

Thormark, C. (2000). Environmental analysis of a building with reused building materials. *International Journal of Low Energy & Sustainable Building*, *1*.

Union, I. (2014). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions*. http://www.xploit-eu.com/pdfs/Europe

Vefago, L. H. M., & Avellaneda, J. (2013). Recycling concepts and the index of recyclability for building materials. *Resources, Conservation and Recycling*, *72*, 127-135.

Wang, L., Lv, Y., Huang, S., Liu, Y., Li, X. (2023). The evolution of research on C&D waste and sustainable development of resources: a bibliometric study. *Sustainability*, *15*, 9141.

Yuan, R., Guo, F., Qian, Y., Cheng, B., Li, J., Tang, X., & Peng, X. (2022). A system dynamic model for simulating the potential of prefabrication on construction waste reduction. *Environmental Science and Pollution Research*, *29*(9), 12589-12600.

Zairul, M. (2021). The recent trends on prefabricated buildings with circular economy (CE) approach. *Cleaner Engineering and Technology*, *4*, 100239.

Comparative Analysis of Wooden Building Systems in Terms of Cost and Energy Efficiency

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Abstract

This study comparatively examines low-rise buildings constructed with wood under different structural systems, focusing on "cost" and "energy efficiency." Two distinct types of wooden construction systems were selected for the analysis: Infilled Wooden and Timber Frame constructions. Within this scope, both types of structures were adapted to a sample residential project with identical architecture and construction area, and relevant analyses were performed. The necessary work items for each construction system were identified, and their quantities were measured for the analysis. Cost analysis was conducted using unit prices published by the Ministry of Environment, Urbanization and Climate Change, as well as the General Directorate of Foundations. For the energy analysis, the Revit software was utilized. The results obtained were compared and presented. The study identifies the advantages and disadvantages of wooden construction systems and evaluates their contribution to sustainable construction projects. Additionally, this research aims to provide an alternative perspective for decision-makers in planning emergency housing post-earthquake.

Keywords: *cost estimation, earthquake housing, energy analysis, sustainability, wooden construction systems.*

Introduction

Timber Frame Structures and Infilled Wooden Structures offer sustainable solutions that are in harmony with architectural and environmental dynamics. These constructions not only provide aesthetic compatibility but also offer ecological advantages, making them stand out in the modern construction industry. Moreover, they meet the demand for eco-friendly materials and energy efficiency. In sustainable construction projects, these types of wooden structures can offer significant benefits in terms of cost and energy consumption. Therefore, a detailed evaluation of the cost and energy efficiency of Timber Frame and Infilled Wooden Construction will encourage their broader application.

In regions with high seismic activity, such as Turkey, Timber Frame and Baghdadi Timber Structure systems can be used to reliably meet both temporary and permanent housing needs. These structures are notable for their rapid construction capabilities after earthquakes, addressing urgent housing needs while also being considered for long-term housing solutions. Early-stage analyses demonstrate the potential of these wooden structures to provide quick and effective housing after disasters.

When examining literature on Wooden Building Systems, it is noted that the study conducted by Konovalov and Kozinets (2019) focuses on the construction of multi-story wooden buildings in Russia. This study involves the development of structural systems and compares the strength, technical, and economic indicators between wooden and reinforced concrete structures. Konovalov and Kozinets (2019) are valuable sources in this regard, while Barrios et al. (2021) in their study on "Tenso-Wood" have made significant suggestions regarding sustainable wooden house construction using low-technology processes. Fire safety poses significant challenges for the widespread application of wooden structures. Frangi and Fontana (2005) offer effective solutions for protecting wooden structures from fire, while Sauerbier et al. (2020) suggest promising alternatives like phosphorus and nitrogen for fire retardant treatments.

In terms of energy efficiency and sustainability, studies have been conducted on the energy consumption and carbon storage potential of wooden structures (Arumägi & Kalamees, 2014; Ahmed & Arocho, 2021). Liang et al. (2021) compared the costs of wooden and concrete structures, finding that the cost of wooden structures was 6.43% higher than that of concrete structures, contributing 5.62% to the total cost of the wooden building. Smith et al. (2018) demonstrated that mass timber constructions provide significant improvements in cost and timing compared to traditional structures. Based on these studies, various aspects of the cost and sustainability characteristics of wooden structures can be understood and compared.

In this study, a housing project has been adapted according to Timber Frame and Infilled Wooden Construction, followed by cost calculations and energy analyses. Cost calculations were performed using the unit price method to estimate approximate costs, while energy analyses were conducted using the Revit program. This study, which comparatively examines low-rise buildings with Timber Frame and Infilled Wooden structural systems in terms of "cost" and "energy efficiency," also aims to provide suggestions for emergency housing planning after earthquakes.

Methodology

This study deals with two different dwellings with the same architectural projects, Timber Frame Construction and Infilled Wooden Construction, in a designated area in Kahramanmaraş province. It is aimed to analyze and compare these two houses, whose only difference is the type of construction system they have, in terms of "cost" and "energy efficiency". The steps of the study, as shown in Figure 1, are the creation of architectural projects, preparation of bill of quantities, calculation of costs and energy analysis.

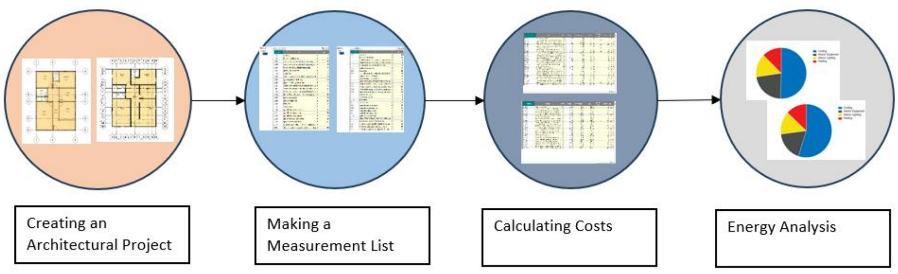

Figure 1: The methodology of the study.

Creating an Architectural Project

For both building systems, architectural projects were drawn in accordance with the land with coordinates 37°60 N and 36°98 E in Kahramanmaraş province. The project is a single-story residential project covering an area of 140 m^2. Revit program was used to draw the architectural projects and care was taken to ensure that the projects have enough comfort area for a family of 5 people. The project types of Timber Frame Construction and Infilled Wooden Construction building systems are shown in Figure 2, respectively.

Timber Frame Construction | Infilled Wooden Construction

Figure 2: Types of wooden structures modelled on land.

Making a Measurement List

e-HakedişPro program was used for the quantity calculations of both building systems. With the measurements taken from the project, bill of quantities for Timber Frame Construction and Infilled Wooden Construction building systems were created as shown in Figure 3a and Figure 3b, respectively.

Ahşap Yığma Yapı
İnşaat İşleri
Adını Giriniz - 2

Poz No	Tanımı	Birimi	Toplam
10.420.1802	Ankraj kon takımı 12 Ø 8	Adet	25,000
15.120.1001	Makine ile yumuşak ve sert toprak kazılması (Serbest kazı)	m³	148,901
15.150.1003	Beton santralinde üretilen veya satın alınan ve beton pompasıyla basılan, C 16/20 basınç dayanım sınıfında, gri renkte,	m³	19,829
15.150.1006	Beton santralinde üretilen veya satın alınan ve beton pompasıyla basılan, C 30/37 basınç dayanım sınıfında, gri renkte,	m³	92,183
15.160.1004	Ø 14- Ø 28 mm nervürlü beton çelik çubuğu, çubukların kesilmesi, bükülmesi ve yerine konulması	Ton	4,000
15.180.1002	Ahşaptan düz yüzeyli beton ve betonarme kalıbı yapılması	m²	33,020
15.210.1004	Ocak taşı ile blokaj yapılması	m³	19,829
15.255.1009	3 mm ve 4 mm kalınlıkta elastomer esaslı (-20 soğukta bükülmeli) polyester keçe taşıyıcılı polimer bitümlü örtüler ile iki k	m²	184,365
15.300.1002	Ahşaptan oturtma çatı yapılması (çatı örtüsünün altı OSB/3 kaplamalı)	m²	157,463
15.325.1001	Ahşap çatı üzerine 0,50 mm kalınlıkta 10 nolu çinkodan çatı örtüsü yapılması	m²	157,463
15.330.1007	Eğimli çatılarda, çatı örtüsü altına, 3 mm kalınlıkta elastomer esaslı, polyester keçe taşıyıcılı polimer bitümlü örtü (-20 C s	m²	157,463
15.341.4003	Çatı arasına döşeme üzerine uygulamalar için, 0,035 < Isıl iletkenliği < 0,040W/(m.K) olan, 8 cm kalınlıkta bir yüzü cam	m²	157,463
15.375.1054	(42,5x42,5 cm) veya (45x45 cm) anma ebatlarında, her türlü desen ve yüzey özelliğinde, I.kalite, renkli seramik yer ka	m²	10,110
15.380.1056	(20x60 cm) veya (30x60 cm) veya (33x60 cm) anma ebatlarında, her türlü desen ve yüzey özelliğinde, I.kalite, renkli	m²	67,800
15.465.1001	Gömme iç kapı kilidinin yerine takılması (Geniş Tip)	Adet	9,000
15.465.1008	Kapı kolu ve aynalarının yerine takılması (Kromajlı)	Adet	9,000
15.465.1010	Menteşenin yerine takılması	Adet	27,000
15.475.1001	Kadronlu ahşap döşeme yapılması	m²	139,725
15.510.1002	Ahşaptan masif tablalı dış kapı kasa ve pervazı yapılması yerine konulması	m²	3,080
15.510.1101	Ahşaptan masif tablalı iç kapı kanadı yapılması ve yerine konulması	m²	15,840
15.510.1102	Ahşaptan masif tablalı dış kapı kanadı yapılması ve yerine konulması	m²	2,420
15.515.1001	Ahşaptan kasa ve pervazlı tek satıhlı pencere yapılması ve yerine konulması	m²	31,680
15.540.1015	Ahşap yüzeylerin vernikli renkli ahşap koruyucu ile verniklenmesi	m²	744,060
43.670.1105	iki komponentli çimento esaslı su geçirimsiz elastik kaplama malzemesi ile ıslak hacimlerde 2,5 mm kalınlığında su yalıtımı	m²	10,110
V.0208/004	I. Kalite çam kereste ile ahşap imalatta kereste ve işçilik bedeli (100 cm²<kesit alanı<225 cm²'den küçük keresteler için)	m³	18,851

Figure 3a: Measurement list of Timber Frame Construction.

Bağdadi Ahşap Yapı
Adını Giriniz - 1
Adını Giriniz - 2

Poz No	Tanımı	Birimi	Toplam
10.420.1802	Ankraj kon takımı 12 Ø 8	Adet	25,000
15.120.1001	Makine ile yumuşak ve sert toprak kazılması (Serbest kazı)	m³	148,901
15.150.1003	Beton santralinde üretilen veya satın alınan ve beton pompasıyla basılan, C 16/20 basınç dayanım sınıfında, gri renkte,	m³	19,039
15.150.1006	Beton santralinde üretilen veya satın alınan ve beton pompasıyla basılan, C 30/37 basınç dayanım sınıfında, gri renkte,	m³	92,183
15.160.1004	Ø 14- Ø 28 mm nervürlü beton çelik çubuğu, çubukların kesilmesi, bükülmesi ve yerine konulması	Ton	8,000
15.180.1002	Ahşaptan düz yüzeyli beton ve betonarme kalıbı yapılması	m²	33,020
15.210.1004	Ocak taşı ile blokaj yapılması	m³	19,829
15.255.1009	3 mm ve 4 mm kalınlıkta elastomer esaslı (-20 soğukta bükülmeli) polyester keçe taşıyıcılı polimer bitümlü örtüler ile iki k	m²	184,365
15.300.1002	Ahşaptan oturtma çatı yapılması (çatı örtüsünün altı OSB/3 kaplamalı)	m²	157,463
15.325.1001	Ahşap çatı üzerine 0,50 mm kalınlıkta 10 nolu çinkodan çatı örtüsü yapılması	m²	157,463
15.330.1007	Eğimli çatılarda, çatı örtüsü altına, 3 mm kalınlıkta elastomer esaslı, polyester keçe taşıyıcılı polimer bitümlü örtü (-20 C s	m²	157,463
15.341.4003	Çatı arasına döşeme üzerine uygulamalar için, 0,035 < Isıl iletkenliği < 0,040W/(m.K) olan, 8 cm kalınlıkta bir yüzü cam	m²	157,463
15.341.4043	6 cm kalınlıkta camyünü levhalar ile bölme duvar, yükseltilmiş döşeme, asma tavan vb. diğer detaylarda ısı ve ses yalıtı	m²	641,653
15.375.1054	(42,5x42,5 cm) veya (45x45 cm) anma ebatlarında, her türlü desen ve yüzey özelliğinde, I.kalite, renkli seramik yer ka	m²	12,183
15.380.1056	(20x60 cm) veya (30x60 cm) veya (33x60 cm) anma ebatlarında, her türlü desen ve yüzey özelliğinde, I.kalite, renkli	m²	68,400
15.465.1001	Gömme iç kapı kilidinin yerine takılması (Geniş Tip)	Adet	9,000
15.465.1008	Kapı kolu ve aynalarının yerine takılması (Kromajlı)	Adet	9,000
15.465.1010	Menteşenin yerine takılması	Adet	27,000
15.475.1001	Kadronlu ahşap döşeme yapılması	m²	133,665
15.510.1001	Ahşaptan masif tablalı iç kapı kasa ve pervazı yapılması yerine konulması	m²	15,840
15.510.1002	Ahşaptan masif tablalı dış kapı kasa ve pervazı yapılması yerine konulması	m²	2,420
15.510.1101	Ahşaptan masif tablalı iç kapı kanadı yapılması ve yerine konulması	m²	14,960
15.510.1102	Ahşaptan masif tablalı dış kapı kanadı yapılması ve yerine konulması	m²	2,420
15.540.1015	Ahşap yüzeylerin vernikli renkli ahşap koruyucu ile verniklenmesi	m²	705,660
43.670.1105	iki komponentli çimento esaslı su geçirimsiz elastik kaplama malzemesi ile ıslak hacimlerde 2,5 mm kalınlığında su yalıtımı	m²	12,273
KTB.51.4002	Duvar, çelik profillerle oluşturulmuş ızgara veya yapı yüzeyine OSB/3(18mm) kaplama yapılması	m2	1.419,150
V.0208/004	I. Kalite çam kereste ile ahşap imalatta kereste ve işçilik bedeli (100 cm²<kesit alanı<225 cm²'den küçük keresteler için)	m³	21,285
V.1667	Kıtıklı veya keçi kıllı kireç harcı ile bağdadı veya diğer ahşap veya kargir düz satıhlar üzerine sıva yapılması	m²	55,944
V.1990/C	2.5 cm kalınlıkta asgari 16 cm genişliğinde lamba zıvanalı, profilsiz düz ahşap tavan veya saçak altı tavan yapılması	m²	431,022

Figure 3b: Measurement list of Infilled Wooden Construction.

Approximate Cost

Table 1a and Table 1b present the approximate cost calculations prepared using the unit price poses published by the Ministry of Environment, Urbanization and Climate Change and the General Directorate of Foundations.

Table 1a: Approximate cost of Timber Frame Construction.

No	Pose Number	Definition	Unit	Quantity	Unit Price (₺)	Amount (₺)
1	10.420.1802	Anchor cone set 12 Ø 8	pieces	25,00	90,00	2.250,00
2	15.120.1001	Excavation of soft and hard soil with	m³	148,901	26,84	3.996,50

		machinery (Open excavation)				
3	15.150.1003	Pouring of normal ready-mixed concrete, grey in color, with a compressive strength class of C 16/20, produced or purchased at a concrete batching plant and pumped using a concrete pump (including concrete transport)	m³	19,829	1.634,89	32.418,23
4	15.150.1006	Pouring of normal ready-mixed concrete, grey in color, with a compressive strength class of C 30/37, produced or purchased at a concrete batching plant and pumped using a concrete pump (including concrete transport).	m³	92,183	1.772,39	163.384,23
5	15.160.1004	Ø 14- Ø 28 mm ribbed concrete steel bar, cutting, bending, and placement of the bars	Ton	4,000	25.828,9 5	103.315,80
6	15.180.1002	Construction of flat-surfaced concrete and reinforced concrete forms from wood	m²	33,02	340,68	11.249,25
7	15.210.1004	Blocking with quarry stones	m³	19,829	547,24	10.851,22
8	15.255.1009	Waterproofing with two layers of polymer-modified bituminous sheets, based on elastomers, featuring a polyester felt carrier, with thicknesses of 3 mm and 4 mm, flexible at -20°C	m²	184,36	287,30	52.968,06

9	15.300.1002	Construction of a timber flat roof (with OSB/3 cladding underneath the roofing material)	m²	157,46	610,11	96.069,75
10	15.325.1001	Installation of a roofing cover made of 0.50 mm thick No. 10 zinc on a wooden roof.	m²	157,46	1.027,99	161.870,39
11	15.330.1007	Waterproofing on sloped roofs with a 3 mm thick polymer-modified bituminous sheet based on elastomers, featuring a polyester felt carrier, flexible at -20°C, installed beneath the roof covering.	m²	157,46	166,80	26.264,83
12	15.341.4003	Installation of an 8 cm thick glass wool mat with one side covered in glass veil, having a thermal conductivity between 0.035 and 0.040 W/(m·K), in attic floors for applications, topped with a vapor-permeable waterproofing membrane	m²	157,46	145,04	22.838,43
13	15.375.1054	Installation of first quality, colored ceramic floor tiles, with any type of pattern and surface feature, in nominal sizes of (42.5x42.5 cm) or (45x45 cm), laid with 3 mm joint spacing using tile adhesive	m²	10,11	330,49	3.341,25
14	15.380.1056	Installation of first quality, colored ceramic wall tiles, with any type of	m²	67,80	403,16	27.334,25

		pattern and surface feature, in nominal sizes of (20x60 cm), (30x60 cm), or (33x60 cm), laid with 3 mm joint spacing using tile adhesive				
15	15.465.1001	Replacement of a recessed interior door lock (Wide Type)	pieces	9,000	62,50	562,50
16	15.465.1008	Replacement of door handles and plates (chromed	pieces	9,000	63,75	573,75
17	15.465.1010	Replacement of the hinge	pieces	27,000	10,75	290,25
18	15.475.1001	Construction of a framed wooden flooring	m²	139,72	607,01	84.814,47
19	15.510.1002	Installation of a solid-board external door frame and trim made from wood	m²	3,08	1.289,61	3.972,00
20	15.510.1101	Construction and installation of a solid-board wooden interior door.	m²	15,84	885,09	14.019,83
21	15.510.1102	Construction and installation of a solid-board wooden exterior door	m²	2,42	1.166,38	2.822,64
22	15.515.1001	Construction and installation of a single-sash wooden window with frame and trim	m²	31,68	1.042,56	33.028,30
23	15.540.1015	Varnishing of wooden surfaces with a colored varnish wood protector	m²	744,06	112,13	83.431,45
24	43.670.1105	Waterproofing of wet areas with a 2.5 mm thick layer of two-component, cement-based, impermeable elastic coating material.	m²	10,11	212,44	2.147,77

25	V.0208/004	Cost of lumber and labor for woodworking with first quality pine timber (for timber sections smaller than 225 cm² and larger than 100 cm²)	m³	18,851	26.840,63	505.972,72
					Total	**1.449.787,87**

Table 1b: Approximate cost of Infilled Wooden Construction.

No	Pose Number	Definition	Unit	Quantity	Unit Price (₺)	Amount (₺)
1	10.420.1802	Anchor cone set 12 Ø 8	pieces	25,00	90,00	2.250,00
2	15.120.1001	Excavation of soft and hard soil with machinery (Open excavation)	m³	148,901	26,84	3.996,50
3	15.150.1003	Pouring of normal ready-mixed concrete, grey in color, with a compressive strength class of C 16/20, produced or purchased at a concrete batching plant and pumped using a concrete pump (including concrete transport)	m³	19,039	1.634,89	31.126,67
4	15.150.1006	Pouring of normal ready-mixed concrete, grey in color, with a compressive strength class of C 30/37, produced or purchased at a concrete batching plant and pumped using a concrete pump (including concrete transport).	m³	92,183	1.772,39	163.384,23
5	15.160.1004	Ø 14- Ø 28 mm ribbed concrete steel bar, cutting, bending,	Ton	8,000	25.828,95	206.631,60

		and placement of the bars				
6	15.180.1002	Construction of flat-surfaced concrete and reinforced concrete forms from wood	m^2	33,02	340,68	11.249,25
7	15.210.1004	Blocking with quarry stones	m^3	19,829	547,24	10.851,22
8	15.255.1009	Waterproofing with two layers of polymer-modified bituminous sheets, based on elastomers, featuring a polyester felt carrier, with thicknesses of 3 mm and 4 mm, flexible at -20°C	m^2	184,36	287,30	52.968,06
9	15.300.1002	Construction of a timber flat roof (with OSB/3 cladding underneath the roofing material)	m^2	157,46	610,11	96.069,75
10	15.325.1001	Installation of a roofing cover made of 0.50 mm thick No. 10 zinc on a wooden roof.	m^2	157,46	1.027,99	161.870,39
11	15.330.1007	Waterproofing on sloped roofs with a 3 mm thick polymer-modified bituminous sheet based on elastomers, featuring a polyester felt carrier, flexible at -20°C, installed beneath the roof coverings	m^2	157,46	166,80	26.264,83
12	15.341.4003	Installation of an 8 cm thick glass wool mat with one side covered in glass veil, having a thermal conductivity between 0.035 and 0.040 W/(m·K), in attic floors for applications, topped	m^2	157,46	145,04	22.838,43

		with a vapor-permeable waterproofing membrane				
13	15.341.4043	6 cm thick glass wool boards are used in partition walls, raised floors, suspended ceilings, and other details for thermal and sound insulation. The sound absorption coefficient (average) of these materials is greater than 1.00,)	m²	641,65	206,51	132.507,76
14	15.375.1054	Installation of first quality, colored ceramic floor tiles, with any type of pattern and surface feature, in nominal sizes of (42.5x42.5 cm) or (45x45 cm), laid with 3 mm joint spacing using tile adhesive	m²	12,18	330,49	4.026,36
15	15.380.1056	Installation of first quality, colored ceramic wall tiles, with any type of pattern and surface feature, in nominal sizes of (20x60 cm), (30x60 cm), or (33x60 cm), laid with 3 mm joint spacing using tile adhesive	m²	68,40	403,16	27.576,14
16	15.465.1001	Replacement of a recessed interior door lock (Wide Type)	pieces	9,000	62,50	562,50
17	15.465.1008	Replacement of door handles and plates (chromed	pieces	9,000	63,75	573,75
18	15.465.1010	Replacement of the hinge	pieces	27,000	10,75	290,25

19	15.475.1001	Construction of a framed wooden flooring	m²	133,66	607,01	81.135,99
20	15.510.1001	Replacement of a recessed interior door lock (Wide Type)	m²	15,84	951,03	15.064,32
21	15.510.1002	Installation of a solid-board external door frame and trim made from wood	m²	2,42	1.289,61	3.120,86
22	15.510.1101	Construction and installation of a solid-board wooden interior door.	m²	14,96	885,09	13.240,95
23	15.510.1102	Construction and installation of a solid-board wooden exterior door	m²	2,42	1.166,38	2.822,64
24	15.540.1015	Construction and installation of a single-sash wooden window with frame and trim	m²	705,66	112,13	79.125,66
25	43.670.1105	Varnishing of wooden surfaces with a colored varnish wood protector	m²	12,27	212,44	2.607,28
26	KTB.51.4002	Applying OSB/3 (18mm) cladding to a wall, grid, or structural surface created with steel profiles	m2	1.419,15	247,88	351.778,90
27	V.0208/004	Cost of lumber and labor for woodworking with first quality pine timber (for timber sections smaller than 225 cm² and larger than 100 cm²)	m³	21,285	26.840,63	571.302,81
28	V.1667	Applying plaster on Baghdad-style or other wooden or masonry flat surfaces using lime mortar mixed with hair or straw	m²	55,944	607,93	34.010,04

29	V.1990/C	2.5 cm thick and minimum 16 cm wide flat wooden ceiling with tongue and groove, without profile or ceiling under the eaves Translate English Translate Just Something Else	m²	431,022	1.221,30	526.407,17
					Total	**2.635.654,31**

Result and Discussion

Approximate Cost Analysis

Figure 4 presents the approximate cost values for the Timber Frame Construction and the Infilled Wooden Construction, respectively. The Timber Frame Construction was estimated to cost 1.449.787,87 TL, while the Infilled Wooden Construction was estimated at 2.635.654,31 TL. The analysis reveals that the Timber Frame Construction was constructed at a lower cost. This cost-effectiveness can be attributed to the easier construction process of Timber Frame Construction compared to Infilled Wooden Construction. Timber Frame Construction are built by stacking ready-made solid timbers in a tongue-and-groove fashion to create the structural system. In contrast, the construction of Infilled Wooden Construction involves staged applications. Initially, a wooden skeleton system is established for Baghdadi Timber Structures, followed by sealing the gaps in the structural system with wooden panel walls. These wooden panel walls are constructed by placing glass wool between two wooden panels for thermal and sound insulation. Finally, the wooden panel walls are covered with vertical slats and the walls are plastered with filler plaster. The differences in the implementation of these two construction systems are reflected in the comparative cost analysis, indicating that the diverse applications in Infilled Wooden Construction are correlated with higher construction costs.

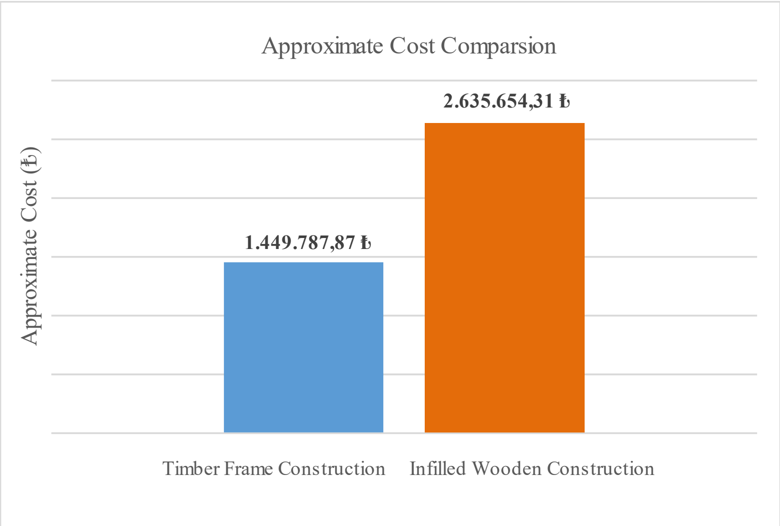

Figure 4: The graph of approximate cost analysis comparison.

Energy Analysis

The graphic in Figure 5 displays the total energy consumption per square meter (kWh/m²) for both the Timber Frame Construction and Infilled Wooden Construction. The energy consumption for the Timber Frame Construction system is calculated at 79.67 kWh/m², while for the Infilled Wooden Construction system, it is found to be 128.45 kWh/m². These values indicate that the energy consumption in the Timber Frame Construction system is lower compared to the Infilled Wooden Construction. This difference can be attributed to the inherent insulation properties of the solid timber used in Timber Frame Constructions. In contrast, the Infilled Wooden Construction uses a wall system comprised of two wooden panels with glass wool in between, covered with a plaster coat, which does not achieve the same level of energy efficiency. The differences in energy consumption between the two construction systems can be attributed to the variations in construction methods and the materials used.

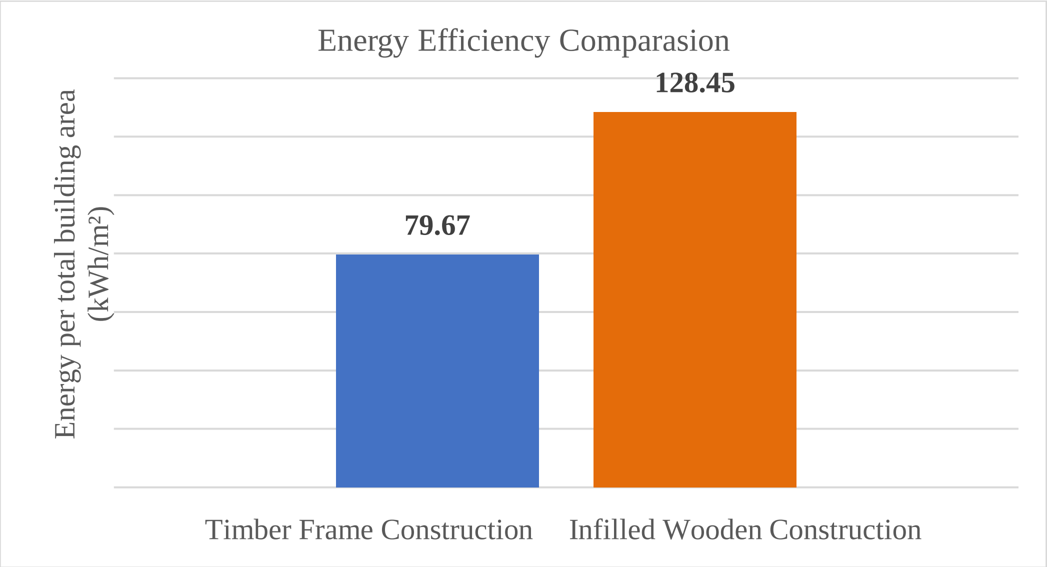

Figure 5: The graph of energy efficiency comparison.

Conclusions

This study examines the "cost" and "energy efficiency" of two single-story buildings designed with the same architecture but employing Timber Frame Construction and Infilled Wooden Construction systems, respectively. The analyses reveal that the building with the Timber Frame Construction system achieves greater energy efficiency at a lower cost. Consequently, it can be stated that buildings with the Timber Frame Construction system are more preferable in terms of these two concepts compared to those with the Infilled Wooden Construction system. This study serves as a preliminary knowledge base for research investigating building systems in sustainable construction practices. Additionally, it will assist researchers engaged in selecting building systems for temporary and permanent housing construction post-earthquake, by providing outputs that offer guidance on cost and energy efficiency.

References

Ahmed, S., & Arocho, I. (2021). Analysis of cost comparison and effects of change orders during construction: study of a mass timber and a concrete building project. *Journal of Building Engineering*, *33*, 101856.

Amiri, A., Ottelin, J., Sorvari, J., & Junnila, S. (2020). Cities as carbon sinks—classification of wooden buildings. *Environmental Research Letters*, *15*(9), 094076.

Arumägi, E., & Kalamees, T. (2014). Analysis of energy economic renovation for historic wooden apartment buildings in cold climates. *Applied Energy*, *115*, 540-548.

Barrios, S., Picón, R., Vargas, M., & Uzcategui, M. (2021). Gerilmiş ahşap panellere dayalı yapısal sistem: deneysel ve sayısal doğrulama. *Tasarım ve Teknoloji*.

Frangi, A., & Fontana, M. (2005). Fire performance of timber structures under natural fire conditions. *Fire Safety Science*, *8*, 279-290.

Konovalov, M., & Kozinets, G. (2019). Prospects for the multi-storey buildings' construction using wooden structures. *IOP Conference Series: Materials Science and Engineering*, *698*(2).

Sauerbier, P., Mayer, A. K., Emmerich, L., & Militz, H. (2020). Fire retardant treatment of wood – state of the art and future perspectives. In L. Makovicka Osvaldova, F. Markert, & S. Zelinka (Eds.), *Wood & Fire Safety*. Springer, Cham.

Smith, R. E., Griffin, G., Rice, T., & Hagehofer-Daniell, B. (2018). Mass timber: evaluating construction performance. *Architectural Engineering and Design Management*, *14*(1-2), 127-138.

A New Proposal for Management of Rebar Works: The Re-Rebar Method

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Abstract

Material management is a crucial component of construction project management. Effective material management requires the economical use of materials, thus contributing to sustainability. Economical use of materials and sustainability can be achieved by reducing material waste to the lowest possible level. A large amount of waste is generated during the construction process of a building. One of the significant wastes generated in this process is rebar waste resulting from cutting losses. In this study, a new method is proposed to reduce rebar cutting loss and managing of rebar works which is called "The Re-Rebar". The fundamental of the system tells moving all rebar works to the factories from the construction sites. In other words, from designing of the project, it is aimed to occur by planning these processes of cutting and installation of rebar and optimizing the stocking of rebar to result in minimum material cost. The planning process is based on BIM methods. In addition, for reducing rebar waste, The Re-Rebar method also contributes positively to occupational safety and stock costs.

Keywords: *material management, optimization, project management, rebar waste, sustainability.*

Introduction

Material management is one of the most crucial components of construction management. Effective management involves optimizing the economic use of materials and contributing to sustainability. Achieving economic use and sustainability requires minimizing material waste.

The construction industry is notorious for generating significant waste. Therefore, proper material management and waste reduction are of paramount importance in this sector (Can & Taş, 2021). According to the UK Statistics on Waste (2020) report, 53.6% of the waste produced in the UK in 2020 was related to construction and demolition. In the United States, construction waste constitutes approximately 23% of the total solid waste (Mills, 1999).

Research indicates that waste generated on construction sites accounts for 4% to 30% of the total material weight delivered to the site (Fishbein, 1998; Mercader-Moyano & Ramírez, 2013). A significant portion of construction site waste falls into the category of one-dimensional material waste. Gavilan's (1992) study revealed that approximately 25% of the waste was 1-D material waste. Minimizing rebar waste is essential not only for the project's economy but also for reducing the country's waste levels.

Among the several types of construction waste, the average proportion of waste from rebar has been reported as follows: 5% in the United States, 3% in China, 21% in Brazil, and 8% in Hong Kong (Chen et al., 2002). Waste generated from rebar is primarily associated with cutting issues (Melega et al., 2018). The objective of cutting optimization for rebar lies in optimizing cutting lengths based on the statically determined dimensions and lengths of rebar specified in the project. This optimization aims to minimize material waste while fulfilling the ordered material requirements (Benjaoran et al., 2019; Khalifa et al., 2006; Kim et al., 2004; Zheng & Lu, 2016).

Numerous studies have addressed solutions to the material cutting problem, typically focusing on two main approaches: analytical approaches and heuristic approaches (Zheng et al., 2019). In analytical approaches, one of the most significant solutions developed for such problems is the approach introduced by Gilmore and Gomory (1961). This method utilizes the column generation technique to create cutting patterns (Arbib et al., 2016; Shahin & Salem, 2004). The computational burden and complexity associated with integer programming have shifted the focus toward heuristic search methods for solving the material cutting problem (Goulimis, 1990; Li et al., 2009). In heuristic approach solutions, the concept of a "sequential heuristic procedure" was first introduced by Haessler (1975) to potentially control cutting losses. Sequentially evaluating cutting patterns ensures that the initially selected patterns are effective in minimizing cutting losses and meeting demand. Gradišar et al. (1999) proposed a hybrid solution combining sequential heuristic procedures with linear programming methods. This solution aims to minimize cutting losses by providing different input lengths for cutting.

Rebar, being a significant component of the construction industry in terms of production, plays a crucial role not only in design and manufacturing (cutting bending) but also in assembly. With advancements in technology, the goal is to manage rebar operations accurately and reduce costs.

Transporting cutting and bending tasks for rebar from construction sites to factories can lead to several benefits, including minimizing scrap rebar generated after cutting, enhancing safety, optimizing labour utilization, and reducing CO_2 emissions. As a result, cost reduction leads to increased profitability.

Material and Method

Traditional construction methods often adhere to specific norms. One common practice involves ordering 12-meters stock rebar for construction projects and performing the manufacturing (cutting and bending) on-site. According to the Unit Price Analysis (2024) by the Republic of Turkey Ministry of Environment, Urbanization, and Climate Change, the waste rate for rebar using this conventional method is estimated to be between 5% and 7%.

The cutting problem associated with rebar is referred to as a 1-D material cutting optimization problem (Salem et al., 2007). Research indicates that 1-D material cutting problems are inherently combinatorial problems. Consequently, genetic algorithms are often recommended for solving combinatorial problems where selections need to be made from numerous pieces (Braga et al., 2015; Lu & Huang, 2015). However, in more complex scenarios, combining genetic algorithm solutions with fuzzy logic systems has been shown to yield more accurate results (Laribi et al., 2004).

The Re-Rebar system focuses on the transportation of rebar manufacturing from on-site to off-site locations. In the traditional approach, rebar manufacturing on-site typically results in the entire trim loss being classified as scrap. However, the Re-Rebar method diverges from other approaches by not optimizing all the required rebar for a project in a single step. Instead, the project is divided into stages based on on-site planning considerations, with each stage representing the site's specific demands. Within each stage, the necessary rebar is optimized independently. This approach ensures that site priorities are considered while achieving more manageable optimization results for manufacturing and stock management.

In the Re-Rebar method, cutting waste is categorized into two types: scrap and offcut. Offcuts represent the portion of rebar resulting from cutting losses in each stage. These offcuts can be evaluated and repurposed in subsequent stages or future projects. This practice is particularly advantageous for workshops or factories compared to on-site solutions. When manufacturing occurs on-site, transporting offcuts to a different construction site is often impractical and may incur additional costs. In contrast, off-site manufacturing areas allow for the evaluation of offcuts across different stages or projects, ultimately reducing the overall scrap quantity.

The Re-Rebar system not only addresses safety concerns related to on-site manufacturing, vehicle traffic within construction sites, and security but also contributes positively to project finance management by spreading out the rebar procurement process over time. Additionally, by ensuring that manufactured rebar arrives at the construction site during the assembly phase, the system facilitates just-in-time (JIT) production.

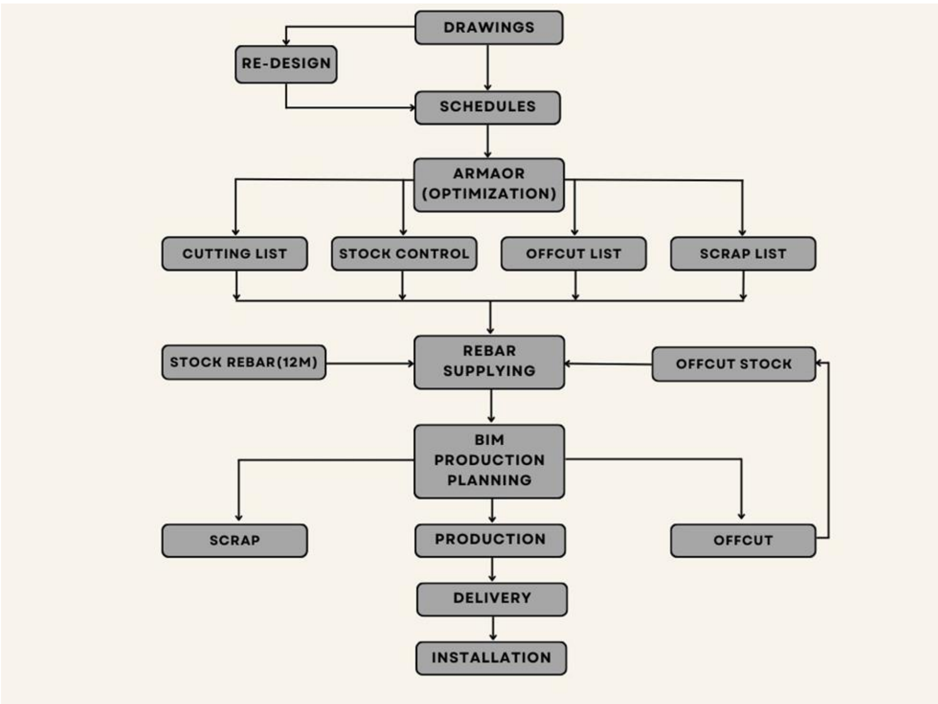

Figure 1: Re-rebar method flow chart.

Another challenge with the traditional method is that after concrete and structural design, the cutting sequence, cutting lengths, scrap quantities, or considerations for later use of rebar are not optimized before delivering the rebar cutting list directly to the implementer. What may be suitable from a design perspective might not be practical for on-site implementation. Consequently, the traditional approach can lead to delays during the construction process. As a result, projects often undergo multiple revisions until completion. Each revision that arises after the manufacturing process has started poses a challenge for construction management.

While creating the Re-Rebar system, 9 basic principles were taken into consideration: Integrity, Optimization, Efficiency, Speed, Standardization, Quality, Profitability, Occupational Safety, and Sustainability. The Re-Rebar System is a process that starts with the receipt of the application projects and ends with the installation of the rebar and consists of 9 basic stages based on BIM and optimization: Redesign, Schedules, Optimization, Cutting List, Supplying, Production Planning, Production, Delivery, and Installation.

Case Study

For this study, three different construction projects have been analyzed using both the traditional method and Re-Rebar. In the traditional method, the following scenario is followed: project approval, extraction of the rebar list, determination of rebar tonnage for each diameter, ordering a slightly excess amount of rebar, planning to cut and bend the incoming stock rebar only for the next concrete casting on-site, and installation. This excess quantity varies depending on the project size, it is ordered at least 5% of the project tonnage. Additionally, for unforeseen situations (project errors, external manufacturing, cutting-bending errors), the rebar weight is rounded to a specific number. The rounded order depends on the experience of the ordering authority. This method is applied in almost all projects that are not very budget-intensive and do not follow a strictly planned approach. Below, relevant data for three projects are presented where rebar orders were placed using the classical method. The stock rebar length is considered to be 12 meters, and scrap below 100 mm. The necessary data for planning the rebar for each diameter and these projects using the traditional method are shown in Table 1.

Table 1. Rebar ordering analysis for traditional method by project.

PROJECT 1	Diameter(mm)	10	12	14	16	20	22	25	28	TOTAL
	Total Weight of 3 Projects(kg)	659.99	75,686.27	9,376.15	46,817.29	64,951.84	24,374.47	71,536.91	8,796.11	302,199.02
	Scrap Weight(Government)	33.00	3,784.31	656.33	3,277.21	4,546.63	1,706.21	5,007.58	615.73	19,627.01
	Scrap Rate(Government)	5.0%	5.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	6.50%
	Scrap+Bar Weight(Government)	692.99	79,470.58	10,032.48	50,094.50	69,498.47	26,080.68	76,544.49	9,411.84	321,826.02
	Rounded Weight(Stock Bar to Order)	1,000.00	80,000.00	10,000.00	50,000.00	70,000.00	26,000.00	78,000.00	10,000.00	325,000.00
	Scrap Weight(Rounded Value)	340.01	4,313.73	623.85	3,182.71	5,048.16	1,625.53	6,463.09	1,203.89	22,800.98
	Scrap Rate(Rounded Value)	51.5%	5.7%	6.7%	6.8%	7.8%	6.7%	9.0%	13.7%	7.55%
	Rounded Difference	307.01	529.42	- 32.48	- 94.50	501.53	- 80.68	1,455.51	588.16	3,173.98
PROJECT 2	Diameter(mm)	10	12	14	16	20	22	25	28	TOTAL
	Total Weight of 3 Projects(kg)	412.89	171,393.31	5,321.00	155,642.00	269,805.00	51,152.88	313,218.00	546.61	967,491.69
	Scrap Weight(Government)	20.64	8,569.67	372.47	10,894.94	18,886.35	3,580.70	21,925.26	38.26	64,288.29
	Scrap Rate(Government)	5.0%	5.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	6.50%
	Scrap+Bar Weight(Government)	433.53	179,962.98	5,693.47	166,536.94	288,691.35	54,733.58	335,143.26	584.87	1,031,779.98
	Rounded Weight(Stock Bar to Order)	1,000.00	180,000.00	6,000.00	168,000.00	290,000.00	56,000.00	336,000.00	1,000.00	1,038,000.00
	Scrap Weight(Rounded Value)	587.11	8,606.69	679.00	12,358.00	20,195.00	4,847.12	22,782.00	453.39	70,508.31
	Scrap Rate(Rounded Value)	142.2%	5.0%	12.8%	7.9%	7.5%	9.5%	7.3%	82.9%	7.29%
	Rounded Difference	566.47	37.02	306.53	1,463.06	1,308.65	1,266.42	856.74	415.13	6,220.02
PROJECT 3	Diameter(mm)	10	12	14	16	20	22	25	28	TOTAL
	Total Weight of 3 Projects(kg)	20,155.32	18,220.27	57,232.20	29,250.64	23,192.63	37,058.78	39,350.54	-	224,460.38
	Scrap Weight(Government)	1,007.77	911.01	4,006.25	2,047.54	1,623.48	2,594.11	2,754.54	-	14,944.71
	Scrap Rate(Government)	5.0%	5.0%	7.0%	7.0%	7.0%	7.0%	7.0%	0.0%	5.63%
	Scrap+Bar Weight(Government)	21,163.09	19,131.28	61,238.45	31,298.18	24,816.11	39,652.89	42,105.08	-	239,405.09
	Rounded Weight(Stock Bar to Order)	22,000.00	20,000.00	62,000.00	32,000.00	26,000.00	40,000.00	44,000.00	-	246,000.00
	Scrap Weight(Rounded Value)	1,844.68	1,779.73	4,767.80	2,749.36	2,807.37	2,941.22	4,649.46	-	21,539.62
	Scrap Rate(Rounded Value)	9.2%	9.8%	8.3%	9.4%	12.1%	7.9%	11.8%	0.0%	9.60%
	Rounded Difference	836.91	868.72	761.55	701.82	1,183.89	347.11	1,894.92	-	6,594.91

When the collected data is analyzed, the resulting conclusion will be as follows.

Table 2. Rebar ordering analysis for traditional method of 3 projects.

	Diameter(mm)	10	12	14	16	20	22	25	28	TOTAL
TOTAL WEIGHT OF 3 PROJECTS	Total Weight of 3 Projects(kg)	21,228.20	265,299.85	71,929.35	231,709.93	357,949.47	112,586.13	424,105.45	9,342.72	1,494,151.09
	Scrap Weight(Government)	1,061.41	13,264.99	5,035.05	16,219.70	25,056.46	7,881.03	29,687.38	653.99	98,860.02
	Scrap Rate(Government)	5.0%	5.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	6.50%
	Scrap+Bar Weight(Government)	22,289.61	278,564.84	76,964.40	247,929.62	383,005.93	120,467.15	453,792.83	9,996.71	1,593,011.10
	Rounded Weight(Stock Bar to Order)	24,000.00	280,000.00	78,000.00	250,000.00	386,000.00	122,000.00	458,000.00	11,000.00	1,609,000.00
	Scrap Weight(Rounded Value)	2,771.80	14,700.15	6,070.65	18,290.07	28,050.53	9,413.87	33,894.55	1,657.28	114,848.91
	Scrap Rate(Rounded Value)	13.1%	5.5%	8.4%	7.9%	7.8%	8.4%	8.0%	17.7%	7.69%
	Rounded Difference	1,710.39	1,435.16	1,035.60	2,070.38	2,994.07	1,532.85	4,207.17	1,003.29	15,988.90

When calculating the weight of rebar to be ordered using the traditional method, the results can be misleading due to disregarding rebar cutting plans. The ordered quantity may fall below what is required for these projects, potentially misleading contractors. During the ordering process, deviations from construction management guidelines can occur due to rounding values.

For the three projects, which have a total weight of 1,494,151 kg, ordering 1,609,000 kg of 12-meters stock rebar will yield 114,848 kg of scrap rebar. However, these quantities are approximate and rounded, so they do not accurately reflect the true requirements. In the end, there will be a need for more rebar than initially calculated. To determine this need, a systematic approach is necessary. When the manufacturing of these projects using the Re-Rebar method was made a scenario, different results were obtained compared to the traditional method. Initially, it was assumed that the first three contracts undertaken by a newly established factory for implementing the Re-Rebar method correspond to Project 1 (Prj-1), Project 2 (Prj-2), and Project 3 (Prj-3). Optimization is performed based on transporting 90 tons in each shipment.

In Prj-1, total rebar weight is 302,199 kg., and optimized stock rebar weight to be used is 324,606 kg. The rebar, which undergoes cutting and bending in workshop manufacturing and is divided into stages according to on-site usage, will be transported to the construction site in a total of 4 transportation operations. Since this is the first project undertaken by the new factory, only 12-meter-long rebar will be used in the initial stage of Prj-1. In Prj-1, the surplus materials from the rebar production are divided into two categories: Off-Cut, and Scrap. In this study, rebar shorter than 90 cm is classified as scrap. The separated scrap material is sent to the scrap stockyard. The optimization results for Prj-1 are presented in Table 1. According to the table, the off-cut ratio in Project 1 is 5.47%, and the scrap ratio is 1.12%.

Table 3. Rebar ordering analysis for the re-rebar method of project 1.

	Diameter(mm)	10	12	14	16	20	22	25	28	TOTAL
PROJECT 1-RE-REBAR	Total Weight of 3 Projects(kg)	659.99	75,686.27	9,376.15	46,817.29	64,951.84	24,374.47	71,536.91	8,796.11	302,199.02
	Required Weight(Stock Bar to Order)	673.77	75,702.35	9,523.87	53,380.25	70,143.77	28,050.89	77,684.50	9,447.48	324,606.88
	Generated Offcut Weight	6.38	13.54	9.85	6,316.29	4,815.98	3,431.52	3,949.77	446.29	18,989.62
	Generated Scrap Weight	7.40	52.71	148.11	352.01	578.28	283.10	2,239.57	218.32	3,879.50
	Rate of Stock Bar Usage	98%	100%	98%	89%	93%	88%	93%	93%	93.42%
	Generated Offcut Rate	0.93%	0.02%	0.10%	10.52%	6.38%	10.80%	4.71%	4.41%	5.47%
	Generated Scrap Rate	1.08%	0.07%	1.53%	0.59%	0.77%	0.89%	2.67%	2.16%	1.12%
	Used Offcut Weight	9.28	2.13	-	257.44	160.42	-	172.85	-	602.12

The total rebar weight for Project 2 is 967,491 kg, and the optimized stock rebar weight to be used is 1,015,233 kg. The material will be transported to the site in 10 transportation operations. In Project 2, the off-cut ratio is 5.28%, and the scrap ratio is 1.07% (Table 2).

Table 4. Rebar ordering analysis for the re-rebar method of project 2.

PROJECT 2-RE-REBAR	Diameter(mm)	10	12	14	16	20	22	25	28	TOTAL
	Total Weight of 3 Projects(kg)	412.89	171,393.31	5,321.00	155,642.00	269,805.00	51,152.88	313,218.00	546.61	967,491.69
	Required Weight(Stock Bar to Order)	429.44	172,526.58	5,868.95	152,961.46	285,182.56	50,627.57	346,767.24	869.40	1,015,233.20
	Generated Offcut Weight	2.47	50.79	534.85	2,837.63	19,978.98	1,056.38	32,437.82	323.61	57,222.53
	Generated Scrap Weight	14.06	1,179.20	54.06	1,196.70	2,445.67	376.87	6,324.68	-	11,591.24
	Rate of Stock Bar Usage	96%	99%	91%	97%	93%	97%	90%	73%	93.65%
	Generated Offcut Rate	14%	4%	8%	2%	6%	2%	8%	27%	5.28%
	Generated Scrap Rate	3%	1%	1%	1%	1%	1%	2%	0%	1.07%
	Used Offcut Weight	-	50.70	41.56	6,714.95	7,047.33	1,878.41	5,213.51	-	20,946.46

The total rebar weight for Project 3 is 224,460 kg, and the optimized stock rebar weight to be used is 236,616 kg. The material will be transported to the construction site in 3 transportation operations. In Project 3, the off-cut ratio is 6.62%, and the scrap ratio is 0.91% (Table 3).

Table 5. Rebar ordering analysis for the re-rebar method of project 3.

PROJECT 3-RE-REBAR	Diameter(mm)	10	12	14	16	20	22	25	TOTAL
	Total Weight of 3 Projects(kg)	20,155.32	18,220.27	57,232.20	29,250.64	23,192.63	37,058.78	39,350.54	224,460.38
	Required Weight(Stock Bar to Order)	20,280.50	18,458.41	58,255.93	30,274.28	22,947.49	35,824.52	50,575.08	236,616.21
	Generated Offcut Weight	33.28	8.92	610.45	2,415.71	2,602.37	632.70	10,645.21	16,948.64
	Generated Scrap Weight	100.24	231.44	815.66	287.27	243.74	57.25	601.68	2,337.28
	Rate of Stock Bar Usage	98.55%	99.60%	97.76%	95.82%	83.58%	0.00%	75.52%	92.46%
	Generated Offcut Rate	0.00%	0.12%	0.19%	3.21%	16.21%	0.00%	22.91%	6.62%
	Generated Scrap Rate	1.45%	0.28%	2.05%	0.97%	0.21%	0.00%	1.57%	0.91%
	Used Offcut Weight	8.34	2.22	402.38	1,679.34	3,091.25	1,924.21	22.35	7,130.09

The total rebar weight for the three projects is 1,494,151 kg. After optimization, the required stock rebar weight is calculated to be 1,576,456 kg. Some of the materials separated as off-cut will be used in subsequent stages and future projects, leaving a remaining off-cut amount of 64,482 kg. This quantity has been moved to the off-cut stockyard for use in upcoming projects.

The total waste weight (off-cut + scrap) for the three projects is 82,290 kg. The overall scrap is 17,808 kg, which is only 15% of the scrap generated using the traditional method (Table 4).

Table 6. Rebar ordering analysis for the re-rebar method of 3 projects.

TOTAL WEIGHT OF 3 PROJECTS	Diameter(mm)	10	12	14	16	20	22	25	28	TOTAL
	Total Weight of 3 Projects(kg)	21,228.20	265,299.85	71,929.35	231,709.93	357,949.47	112,586.13	424,105.45	9,342.72	1,494,151.09
	Required Weight(Stock Bar to Order)	21,383.71	266,687.34	73,648.75	236,615.99	378,273.82	114,502.98	475,026.82	10,316.88	1,576,456.29
	Generated Offcut Weight	42.13	73.25	1,155.15	11,569.63	27,397.33	5,120.60	47,032.80	769.90	93,160.79
	Generated Scrap Weight	121.70	1,463.35	1,017.83	1,835.98	3,267.69	717.22	9,165.93	218.32	17,808.02
	Rate of Stock Bar Usage	99.24%	99.43%	97.13%	94.64%	92.50%	95.15%	89.42%	91.26%	93.42%
	Generated Offcut Rate	0.20%	0.03%	1.52%	4.63%	6.70%	4.26%	8.85%	6.81%	5.52%
	Generated Scrap Rate	0.56%	0.55%	1.34%	0.73%	0.80%	0.60%	1.73%	1.93%	1.06%
	Used Offcut Weight	17.62	55.05	443.94	8,651.73	10,299.00	3,802.62	5,408.71	-	28,678.67

Results

In this study, the Re-Rebar method, recommended by the authors for reducing rebar waste, has been examined. The study utilized the rebar lists of three different-sized projects. First, the losses resulting from traditional methods of ordering the necessary rebar for the fabrication in these three projects were calculated. Then, the losses arising from ordering the same rebar fabrication using the Re-Rebar method were also calculated. Finally, the results obtained from the traditional method were compared with those from the Re-Rebar method. According to the case study covering a total of three projects, when the Re-Rebar method was applied, the amount of scrap produced was 15% of the scrap generated by the traditional method.

The traditional method does not rely on calculations, but it relies on acceptances. Material orders based on acceptance are prone to errors because they overlook the unique conditions of the project. In contrast, the Re-Rebar method is specifically tailored to the project, taking into account all relevant conditions, including intermediate stages. Therefore, the results obtained through the Re-Rebar method are directly applicable in construction sites.

Under the traditional method, rebar fabrication occurs in a designated area on the construction site. Due to reasons such as lack of knowledge about future needs at another site and high transportation costs, the scrap rebar resulting from fabrication is separated as waste. In the Re-Rebar method, however, rebar fabrication takes place in a factory environment. While some of the resulting off-cuts are discarded as scrap, others are set aside for use in subsequent projects.

The improvement that will be achieved as a result of the application of the Re-Rebar method will not only reduce the amount of scrap in rebar, but also various issues such as sustainability, carbon footprint, occupational health and safety, workforce and cost may be the subject of study for future researchers.

References

Arbib, C., Marinelli, F., & Ventura, P. (2016). One-dimensional cutting stock with a limited number of open stacks: bounds and solutions from a new integer linear programming model. *International Transactions of Operational Research*, *23*(1-2), 47-63.

Benjaoran, V., Sooksil, N., & Metham, M. (2019). Effect of demand variations on steel bars cutting loss. *International Journal of Construction Management*, *19*(2), 137-148.

Braga, N., Alves, C., Macedo, R., & Carvalho, J. V. (2015). A model-based heuristic for the combined cutting stock and scheduling problem. *Proceedings of International Conference on Communication Science and its Applications*, pp. 490-505.

Can, G., & Taş, E. F. (2021). Analysis of non-physical waste causes that affect the construction process. *Journal of the Faculty of Engineering and Architecture of Gazi University*, *36*(2), 655-668.

Chen, Z., Li, H., & Wong, C. T. C. (2002). An application of bar-code system for reducing construction wastes. *Automation in Construction*, *11*(5), 521-533.

Fishbein, B. (1998). *Building for the future: strategies to reduce construction and demolition waste in municipal projects*. Inform.

Gavilan, R. M. (1992). *An analysis of construction solid wastes* [PhD thesis]. North Carolina State University.

Gilmore, P. C., & Gomory, R. E. (1961). A linear programming approach to the cutting-stock problem. *Operations Research, 9*(6), 849-859.

Goulimis, C. (1990). Optimal solutions for the cutting stock problem. *European Journal of Operations Research*, *44*, 197-208.

Gradišar, M., Resinovič, G., & Kljajić, M. (1999). Hybrid approach for optimization of one-dimensional cutting. *European Journal of Operations Research*, *119*(3), 719-728.

Haessler, R. W. (1975). Controlling cutting pattern changes in one-dimensional trim problems. *Operations Research*, *23*(3), 483-493.

Khalifa, Y., Salem, O., & Shahin, A. (2006). Cutting stock waste reduction using genetic algorithms. Genetics, Evolution, and Computation Conference, pp. 1675-1680.

Kim, S. K., Hong, W. K., & Joo, J. K. (2004). Algorithms for reducing the waste rate of reinforcement bars. *Journal of Asian Architecture and Building Engineering*, *3*(1), 17-23.

Laribi, M. A., Mlika, A., Romdhane, L., & Zeghloul, S. (2004). A combined genetic algorithm-fuzzy logic method (GA-FL) in mechanisms synthesis. Mechanics and Machinery Theory, *39*(7), 717-735.

Li, Y., Yang, Y., Zhou, L., Zhu, R. (2009). Observations on using problem-specific genetic algorithm for multiprocessor real-time task scheduling. *International Journal of Internal Communication and Information Controlling*, *5*(9), 2531-2540.

Lu, H. C., & Huang, Y. H. (2015). An efficient genetic algorithm with a corner space algorithm for a cutting stock problem in the TFT-LCD industry. *European Journal of Operations Research*, *246*(1), 51-65.

Melega, G. M., de Araujo, S. A., & Jans, R. (2018). Classification and literature review of integrated lot-sizing and cutting stock problems. *European Journal of Operations Research*, *271*(1), 1-19.

Mercader-Moyano, P., & Ramírez-de-Arellano-Agudo, A. (2013). Selective classification and quantification model of C&D waste from material resources consumed in residential building construction. *Waste Management and Research*, *31*(5), 458-474.

Mills, T., Showalter, E., & Jarman, D. (1999). A cost-effective waste management plan. *Cost Engineering*, *41*(3), 35-43.

Salem, O., Shahin, A., & Khalifa, Y. (2007). Minimizing cutting wastes of reinforcement steel bars using genetic algorithms and integer programming models. *Journal of Construction Engineering and Management*, *133*(12), 982-992.

Shahin, A. A., & Salem, O. M. (2004). Using genetic algorithms in solving the one-dimensional cutting stock problem in the construction industry. *Canadian Journal of Civil Engineering*, *31*(2), 321-332.

Zheng, C., & Lu, M. (2016). Optimized reinforcement detailing design for sustainable construction: slab case study. *Procedia Engineering*, *145*, 1478-1485.

Zheng, C., Yi, C., & Lu, M. (2019). Integrated optimization of rebar detailing design and installation planning for waste reduction and productivity improvement. *Automation in Construction*, *101*, 32-47.

Use of Mass Timber in the Construction and Design

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Abstract

Timber has historically played a pivotal role in architecture, valued for its ease of processing, sustainability, and structural qualities. Despite being overshadowed by concrete and steel in recent years, timber is making a global comeback due to its sustainability, lightweight nature, and earthquake resistance. Additionally, timber acts as a carbon sink, emitting minimal carbon, further enhancing its relevance in contemporary architecture amidst global climate agreements and recycling initiatives. Timber contributes to healthier indoor environments by influencing architectural design, especially in the context of biophilic design principles. For this reason, it is believed that combining the basic features of earthquake-resistant traditional timber architecture and the advanced features of mass timber in the design of modern timber structures will have an important place in the future. In this study, the significance of mass timber in architectural design has been explored within the context of biophilic design criteria, addressing the importance of incorporating mass timber in architecture. The advantages and disadvantages of using mass timber in construction and design are highlighted, and the impact of contemporary timber construction techniques is discussed.

Keywords: *biophilic design, sustainability, timber architecture, timber construction, wood.*

Introduction

Developing technology and increasing urbanization have led to a decrease in people's relationship with nature. The psychological and physical effects of the weakening of people's relationship with nature and spending time indoors have been frequently discussed in various academic circles in recent years. In the field of architecture, issues such as the relationship with nature, natural materials and interior quality come to the fore (Erbay, 2021; Jóźwik & Jóźwik, 2021; Özğan & Aluçlu, 2023; Tekin et al., 2023). All of these issues can be examined within the scope of biophilic design principles.

The concept of biophilia is formed by combining the Greek words "bio" meaning living, life, living and "philia" meaning love and positive feelings towards something (Contreras et al., 2023; Nasr Aly Tahoun, 2019). It is possible to consider this concept as love for nature and living things. The concept of biophilia, which was first defined as "love of nature" by Erich

Fromm in 1965, was addressed by biologist Edward Wilson in 1984 as "the human tendency to interact with nature" (Demirkol & Önaç, 2021; Nasr Aly Tahoun, 2019). In 2008, in the book "Building for Life: Designing and Understanding the Human Nature Connection", 72 biophilic design criteria were first stated by Stephen Kellert (Kellert, 2008). In 2015, Kellert and Calabrase simplified and organized them into the currently accepted biophilic design criteria (Kellert & Calabrese, 2015) (Table 1).

Table 1. Experience and attributes of biophilic design (Adapted from Kellert & Calabrese, 2015).

Direct Experience of Nature	Light Air Water Plants Animals Weather Natural landscapes and ecosystems Fire	**Indirect Experience of Nature**	Images of nature Natural materials Natural colors Simulation of natural light and air Naturalistic shapes and forms Evoking nature Wealth of information Age, change, and the patina of time Natural geometries Biomimicry	**Experience of Space and Place**	Prospect and refuge • Organized complexity • Integration of parts to wholes • Mobility and wayfinding • Cultural and ecological attachment to place

These criteria emphasize the importance of the material. Considering the design criteria at the direct, indirect and spatial level, this study is based on timber. The materials to be used in architectural buildings vary according to the location, function, spatial characteristics and structural system preferences of the building. Stone, adobe, wood, reinforced concrete and steel are the prominent construction materials. Today, thanks to the development of engineering systems, chemical materials that protect wood, and modern construction techniques, timber is once again preferred and stands out as a strong alternative to other materials (Çelik & Şakar, 2022; Smith & Snow, 2008). The use of timber and the reasons for their preference can be evaluated under the indirect experience of nature within the scope of biophilic design criteria.

The Paris Climate Agreement signed by 197 countries, including Turkey, in 2015 and the Glasgow Climate Pact signed in 2021 set targets for carbon emissions. By 2030, it is aimed to reduce carbon emissions by 45% compared to 2010 and to zero by mid-century (European Commission, 2019; Tema, 2022). Wood is a building material that emits the least carbon emissions and acts as a carbon sink (Figure 1). This is one of the most important reasons for the reuse of wood in construction works (Puuinfo, 2020).

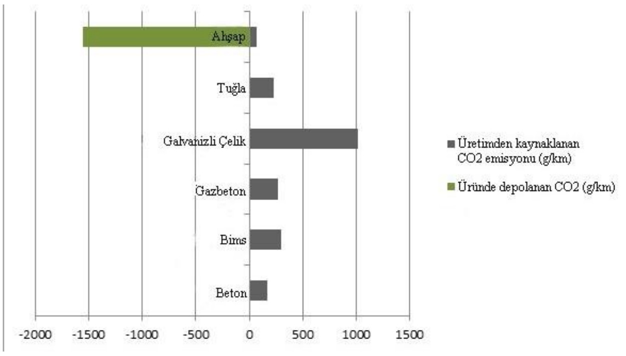

Figure 1: CO generated in the production of different building materials (Puuinfo, 2020).

In addition, timber structures are also important in terms of sustainable life cycle considering issues such as low transportation, low crane fees, low maintenance costs and low demolition costs (Scouse et al., 2020; Türer 2020). Wood, which surpasses other building elements with these features, is considered as the building material of the future (Çelik & Şakar, 2022; Şişman & Ökten, 2023). For this reason, incentive policies have been introduced in various countries (UNECE, 2016). These incentive policies focus on reducing greenhouse gas emissions and/or supporting climate change policies, reducing the environmental impact of construction materials (embodied energy, water, waste, etc.) and/or promoting local wood economy and culture (UNECE, 2016). As a result of incentive policies, countries are developing national regulations and standards. In our country, timber construction standards were determined with the regulation published in 2024 and will enter into force in 2025.

In addition to its advantages, wood also has disadvantages such as fire, decay, being affected by microorganisms, etc. As a result of the study of the disadvantages of timber and the studies carried out to eliminate these disadvantages, mass timber construction materials have emerged (Demirkır, 2021). Although standards on the application methods of mass timber elements have been developed in many countries, experimental studies in this field are still ongoing (Azinovic et al., 2023; Ceylan, 2021; Gao et al., 2023; Rebouças et al., 2022; Trautz et al., 2023). In this study, the spatial and structural effects, economic and environmental benefits of mass timber elements are discussed.

The Place of Mass Timber Elements in Architectural Design

In traditional buildings, the structural system elements of the building and the materials used in ornaments are preferred from local materials (Şahin, 2020). This has enabled traditional buildings to be sustainable and adaptable to the location and climate. Today, in line with the principles of biophilic design; designs are made by combining these features in traditional buildings with current construction technologies and materials (Figures 2 and 3) (The Wood Institute, 2024).

Figure 2: Brock Commons Tallwood House (The Wood Institute, 2024)

Figure 3: T3: Timber, Transit, and Technology (The Wood Institute, 2024)

Mass timber are also frequently used in these designs. With the use of mass timber elements, the limitations of traditional timber systems have started to disappear. Especially the structures where cross-laminated timber and glued laminated timber materials are used are high-rise structures with wide spans. In addition, these structures are lighter than steel or reinforced concrete structures (Van Veelen & Knuth, 2023). This situation is of particular importance in countries like our country, which is located in an earthquake zone.

It is possible to say that wood material exists in buildings in two ways. In addition to the strong structural properties of wood; thanks to the spatial effect it creates, it has been observed that it reduces stress and has positive effects on human psychology (Tekin et al., 2023; Untaru et al., 2024). When the preference of materials such as structural systems where wood is visible, interior spaces where wood is used as decoration, flooring and ceiling coverings etc. in buildings such as hospitals, schools and offices are examined within the scope of biophilic design criteria, it has been determined that the use of wood materials reduces stress, increases motivation and working efficiency (Alik, 2021; Tekin et al., 2023; Untaru et al., 2024).

Compared to other construction materials, mass timber materials are advantageous in terms of construction cost in terms of foundation excavation, construction time, labor cost, even in cases where wood is imported (The Wood Institute, 2024). However, the advantage depends on the supply possibilities of the country where the construction work is carried out, the standards of wood construction, the state of the construction industry (Hassan et al., 2019; Yun, 2012).

In our country, timber has been preferred in all or part of the structural system in traditional buildings, as an ornamental element and in joinery (Şahin, 2020). However, with the increase in reinforced concrete systems, the use of timber in the structural system has decreased. (GEF, 2024). Today, ministries and non-governmental organizations are working on various incentive policies and standards to promote the use of timber. (OGM, 2022). The latest development in our country in this regard is the Ahşap Binaların Tasarım, Hesap ve Yapım Esaslarına Dair Yönetmelik (Regulation on the Design, Calculation and Construction Principles of Wooden Buildings) published in the Resmi Gazete on March 24, 2024 (Resmi Gazete, 2024). Under the main headings such as general provisions, material properties, structural modeling calculation methods, design according to strength, fire resistance, standards for the design and applications to be made using mass timber materials have been determined (Resmi Gazete, 2024). Since this regulation is one of the first studies on the subject, it is open to improvement. Article 4, subparagraph c of the Regulation states that "*Turkish Standards shall be taken as basis for the matters for which there are no adequate provisions in this Regulation, and European Standards shall be taken as basis in the absence of these standards.* In *matters not regulated in Turkish or European Standards, internationally recognized standards may also be used."* (Resmi Gazete, 2024).

Considering issues such as low transportation, crane fees, maintenance costs and demolition costs, timber structures are important in terms of sustainable life cycle and are ahead of other building elements (Scouse et al., 2020; Türer, 2020). In addition to these, considering the climate policies that our country is involved in, it is possible to say that the importance of studies on mass timber elements has increased.

Instead of Conclusion

Timber has been a preferred construction material throughout history due to its ease of transportation, speed of production and high strength. Especially in recent years, the use of timber in the construction sector has started to increase again. The advantages of wood material influence this increase. In general, the advantages and disadvantages of timber are given in Table 2.

Table 2. Advantages and disadvantages of timber.

Advantages	Sustainability/Carbon sequestering features Earthquake resistance Physical and psychological effects Ease/speed of implementation
Disadvantages	Cost Fire Decay/ microorganisms Lack of Knowledge (Practice-Standard-Training)

The advantages and disadvantages of timber may also vary according to the structural system of the building, its location, spatial characteristics, function, economic situation and climate of the place where it is built.

It is possible to say that the common point of the studies in the field is the effect of the use of wood materials on climate, people and nature. The disadvantages of mass timber materials such as fire, decay, cost, lack of information are tried to be eliminated with the studies; earthquake resistance, application speed, sustainability features are also tried to be strengthened.

With the increase in wood use, forests are also expected to increase. As a result, not only the tree population but also other living beings living in the forest will increase. This is important for a sustainable world. When all factors are evaluated; wood stands out as the construction material of the future. This study is expected to contribute to the studies on the effect of mass timber use on architectural design in our country.

References

Alik, B. (2021). *Hastane mimarisinin biyofilik tasarım parametrelerine göre değerlendirilmesi* [PhD thesis]. Kocaeli University.

Azinovic, B., Serrano, E., Danielsson, H., Füssl, J., Lukacevic, M., Dietsch, P., Arnold, M., Schenk, M., Winter, S., Cabrero, J. M., Gonzalez Serna, P., & Pazlar, T. (2023). Innocrosslam - adding knowledge towards increased use of cross laminated timber (CLT). *Proceedings of World Conference on Timber Engineering*, pp. 2432-2441.

Çelik, H. K., & Şakar, G. (2022). Geçmişin ve geleceğin yapı malzemesi olarak ahşap: yapı mühendisliği çerçevesinde bir inceleme. *European Journal of Science and Technology*.

Ceylan, A. (2021). *Çapraz lamine ahşap panel yapı sistemleri ve birleşim özelliklerinin deneysel incelenmesi* [PhD thesis]. Yıldız Technical University.

Contreras, G. S., Lezcano, R. A. G., Fernández, E. J. L., & Pérez Gutiérrez, M. C. (2023). Architecture learns from nature: the influence of biomimicry and biophilic design in building. *Modern Applied Science*, *17*(1), 58.

Demirkır, C. (2021). *Yapısal ahşap ve yeni nesil yapısal ahşap malzemeler*. https://www.ahsap.org.tr/files/ugd/3b2e39d230f3982e60449a95b409e41136c985.pdf

Demirkol, A. K., & Önaç, A. K. (2021). Biyofilik tasarım kriterleri bağlamında ofis tasarımı. *Proceedings of 5th International Students Science Congress*.

Erbay, M. (2021). İç mekânda biyofilik tasarım ve uygulama alanı olarak bir sağlık yapısı: Memorial Bahçelievler Hastanesi. *Kocaeli Üniversitesi Mimarlık ve Yaşam Dergisi*, 529-551.

European Commission (2019). *Going climate-neutral by 2050: a strategic long-term vision for a prosperous, modern, competitive and climate-neutral EU economy*. Publications Office.

Gao, Y., Xuan, S., Xu, F., Diao, Y., & Meng, X. (2023). Shear performance of a novel non-metallic cross-laminated timber wall-to-wall connection using double-dovetail mortise-tenon joint. *Wood Material Science & Engineering*, *18*(3), 1003-1013.

GEF. (2024). *Promoting low-cost energy efficient wooden buildings in Türkiye*. Global Environment Facility.

Hassan, O. A. B., Öberg, F., & Gezelius, E. (2019). Cross-laminated timber flooring and concrete slab flooring: a comparative study of structural design, economic and environmental consequences. *Journal of Building Engineering*, *26*, 100881.

Jóźwik, R., & Jóźwik, A. (2021). Influence of environmental factors on urban and architectural design—example of a former paper mill in Nanterre. *Sustainability*, *14*(1), 86.

Kellert, S. R. (2008). Dimensions, elements, and attributes of biophilic design. In *Biophilic design: the theory, science and practice of bringing buildings to life*.

Kellert, S. R., & Calabrese, E. F. (2015). *The practice of biophilic design*. www.biophilic-design.com

Nasr Aly Tahoun, Z. (2019). Awareness assessment of biophilic design principles application. *IOP Conference Series: Earth and Environmental Science*, *329*(1), 012044.

OGM (2022). *Ahşap kullanımının yaygınlaştırılması projesi*.

Özğan, A. O., & Aluçlu, İ. (2023). Doğayla uyumlu mekânlar: biyofilik tasarımın bibliyometrik değerlendirmesi: *İdealkent*. *15*(41), 483-505.

Puuinfo (2020). *Carbon is bound in wood structures for a long time*. https://puuinfo.fi/puutieto/environmental-and-resource-efficiency/carbon-is-bound-in-wood-structures-for-a-long-time/?lang=en

Rebouças, A. S., Mehdipour, Z., Branco, J. M., & Lourenço, P. B. (2022). Ductile moment-resisting timber connections: a review. *Buildings*, *12*(2), 240.

Resmi Gazete (2024). *Ahşap binaların tasarım, hesap ve yapım esaslarına dair yönetmelik*. https://www.resmigazete.gov.tr/eskiler/2024/03/20240324-1.htm

Şahin, N. (2020). *Ahşap yapılarda taşıyıcı sistem özellikleri ve güçlendirmelerinin Çorum Veli Paşa hanı yapısında incelenmesi* [Master thesis]. Erciyes University.

Scouse, A., Kelley, S. S., Liang, S., & Bergman, R. (2020). Regional and net economic impacts of high-rise mass timber construction in Oregon. *Sustainable Cities and Society*, *61*, 102154.

Şişman, M. E., & Ökten, B. B. (2023). Yapı sektöründe ahşap teşvik politikaları ve etkileri. *Journal of FSMVU Faculty of Architecture and Design*.

Smith, I., & Snow, M. A. (2008). Timber: an ancient construction material with a bright future. *The Forestry Chronicle*, *84*(4), 504-510.

Tekin, B. H., Corcoran, R., & Gutiérrez, R. U. (2023). The impact of biophilic design in Maggie's Centres: a meta-synthesis analysis. *Frontiers of Architectural Research*, *12*(1), 188-207.

Tema (2022). *Glasgow-iklim-pakti*. https://cdn-tema.mncdn.com/Uploads/Cms/glasgow-iklim-pakti.pdf

The Wood Institue (2024). *Design and construction of taller wood buildings*. https://www.woodinstitute.org/mod/book/view.php?id=2386&chapterid=539

Trautz, M., Grizmann, D., Pranjic, A., Raupach, M., Glawe, C., Gillner, A., Bornschlegel, B., & Haasler, D. (2023). Laser predrilling for high-precision positioning and installation of fully threaded screws in glued-laminated timber (glulam). *Wood Material Science & Engineering*, *18*(2), 491-506.

Türer, A. (2020). *Ulusal Ahşap Birliği - Prof. Dr. Ahmet Türer: Eurocode 5: hımış ahşap yapı sistemi*. https://www.youtube.com/watch?v=oyyfa9PVSd8

UNECE (2016). *Promoting sustainable building materials and the implications on the use of wood in buildings*. https://unece.org/DAM/timber/publications/SP-38.pdf

Untaru, E.-N., Han, H., David, A., & Chi, X. (2024). Biophilic design and its effectiveness in creating emotional well-being, green satisfaction, and workplace attachment among healthcare professionals: the hospice context. *HERD: Health Environments Research & Design Journal*, *17*(1), 190-208.

Van Veelen, B., & Knuth, S. (2023). An urban 'age of timber'? Tensions and contradictions in the low-carbon imaginary of the bioeconomic city. *Environment and Planning E: Nature and Space*.

Yun, D. (2012). *Potential opportunities for cross laminated timber in South Korean residential building market*. https://doi.org/10.14288/1.0103131

Sustainable Advancements in Construction: Exploring the Impact of Self-Healing Concrete Technology Utilizing Bacteria

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Abstract

The construction industry plays a crucial role in shaping the sustainability landscape, with a growing emphasis on innovative technologies to address environmental concerns. This study delves into the promising realm of self-healing concrete technology, particularly its integration with bacteria, and examines its transformative impact on sustainability within the construction sector. Self-healing concrete, fortified with microorganisms capable of precipitating minerals, introduces a groundbreaking approach to enhance the durability and longevity of structures. The utilization of bacteria, such as Bacillus spp., embedded in the concrete matrix triggers a biological response to heal cracks autonomously. This technology not only addresses maintenance challenges but also contributes significantly to the reduction of environmental impact and resource consumption associated with frequent repairs. The research explores the mechanisms involved in the self-healing process, shedding light on the biological and chemical reactions that enable concrete to mend itself. Furthermore, it evaluates the ecological implications of adopting such a technology, considering the potential reduction in material waste, extended infrastructure lifespan, and minimized need for energy-intensive repair processes. The potential for decreased maintenance costs, improved structural reliability, and a positive influence on safety align with broader sustainability goals, making it a compelling avenue for future construction practices.

Keywords: *concrete, MICP, mortar, self-healing, sustainability.*

Introduction

Cracking in concrete and cement mixes is an issue of high importance as it affects the mechanical performance as well as the durability of the structures. Conventional methods of the repair of cracks can be expensive and cumbersome. Bio-mineralization is a process that is responsible for what is termed as self-healing in cement-based composites, where microorganisms that can precipitate calcium carbonate (CaCO3) through different metabolic pathways. This calcite helps to seal cracks and boost the mechanical performance of those structures as well as reduce permeability which is responsible for deterioration in durability. However, how long can calcite seal cracks for as well as the biological consequences of using bacteria in concrete in the long run, remain uncertain. Bacillus subtilis bacteria is considered one of the most popular types to be utilized in self-healing concrete and mortar studies.

Concrete and mortar structures are by far the most occurring and favored structures in the world. Their mechanical and durability attributes provides them with those favorable attitudes. However, it is well known that those structures as susceptible to cracking due to a multitude of reasons, weakness in tension, changes in temperatures, drying-shrinkage, and fatigue loading and various environmental conditions. Cracks lead to reductions in strength as well as durability as they increase permeability and allow for the intrusion of moisture and aggressive chemicals that could find their way to the reinforcement that is the key element of sustaining tensile loads. The concept of self-healing, by which concrete and mortar is able to seal some cracks and regain its toughness and remain durable is one of the focused-on topics in literature. Self-healing has been made possible by the autogenous capabilities of the matrix to produce calcium carbonate or calcite (CaCO3) through the hydration of un-hydrated compounds as water infiltrates cracks. But also through autonomous self-healing which occurs due to the introduction of some foreign elements to the matrix that aids in the formation of CaCO3 and sealing of cracks. One of those types of autonomous self-healing is through the addition of bacteria.

The current study represents an extensive review of the effect of this bacteria incorporation on the mechanical properties and durability in detail, as well as the various technical aspects of introducing these bacteria into the mixes. A comparison between the biological techniques of preparing these bacteria whether in viable form or as spores is conducted. The investigation of the methods of introducing the cracks into concrete and mortar mixes when this type of bacteria is used is also highlighted. The goal of this study was to investigate these abovementioned areas in depth and shedding light on the challenges and limitations. Thus, paving the way for further research in the literature.

Significance of MICP (Microbial-Induced Calcite Precipitation) in Self-Healing Mortar

Mechanisms of Self-Healing in Mortar

MICP (Microbial based Calcite Precipitation) which microbial induced calcite precipitation and in the case of bacteria being the microbes added to the matrix, it can happen in two ways either through metabolic pathways of bacteria, the most popular of which is the ureolysis, but there are many others, such as photosynthesis, sulfate reduction, methane oxidation, denitrification and ammonification or the second way is through providing nucleation sites on the surfaces and walls of the bacteria cells with the help of extracellular polymeric substances that are present on those walls to allow for the precipitation of calcite on them (Lee & Park, 2018).

Role of Microorganisms in Self-Healing Materials

The second way is what leads the research of precipitation of calcite on dead bacteria cells. For the bacteria to be able to live in concrete, which is known for its high alkalinity, around pH of 12-13, as well as the high temperature and pressure forming during the hydration process and the insufficiency of oxygen later in the mix, the bacteria has to be able to withstand those environmental factors to remain viable in concrete and continue the metabolic processes as needed (Lee & Park, 2018). Only a few gram-positive groups of bacteria are known to do so, which as the Bacillus group, the sporosarcina group and lysinibacillus groups. Both of the Bacillus and Sporosarcina genera are ureolytic bacteria that are capable of the ureolysis pathway by degrading urea into uric acid with the help of the urease enzyme (Lee & Park, 2018). These two equations better represent what is happening (Özhan & Yıldırım, 2020).

$$CO(NH_2)_2 + 2H_2O \xrightarrow{\text{Bacterial urease enzyme}} 2NH_4^+ + CO_2^{-2} \quad (1)$$

$$Ca^{+2} + CO_3^{-2} \rightarrow CaCO_3 \quad (2)$$

Usually concrete matrices have a pore size less than 1 micrometer and that in less than 1% porosity level. But bacteria size are about 1 to 4 micrometer in size. Bacteria are subject to compression and shear stress in the matrix, too (Lee & Park, 2018).

Generally for bacteria to be able to live in concrete mixes it has to withstand the concrete mix it has to be able to adapt with the high pH values and the long time with no nutrients and low moisture content. It is generally a restrictive environment for bacteria. Bacillus bacteria types are known to be equipped for such environments.

Cracking in concrete is an issue that highly influences the durability and at times even the mechanical performance of structures. The reason behind that is the increased permeability of cracked concrete to fluids and gases that penetrate through them. Those fluids could be water, acids, salts and various others that would lead to corrosion of steel reinforcement. Self-healing concrete has been a suggested solution

Cultivation of Bacteria

There is a variety of cultivation methods available for preparing the bacterial solutions for later-use in self-healing research. One of the varieties the cultivation process can be usually summarized as in Figure 1.

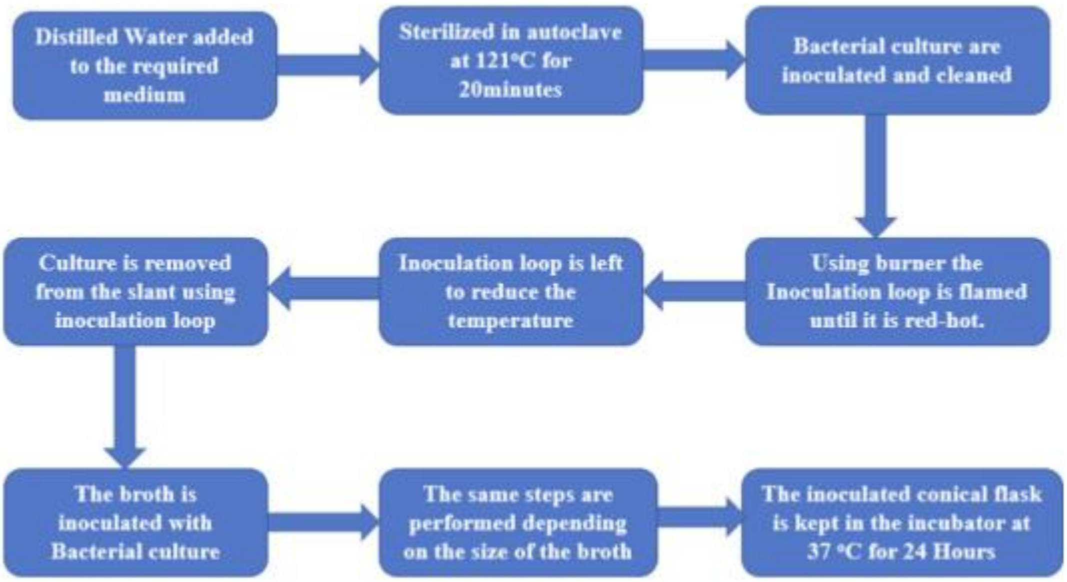

Figure 1: Bacteria cultivation process.

Many others in literature mentioned their chosen process for cultivation of bacteria as can be seen in Table 1.

Table 1. Cultivation methods from literature.

Cultivation Procedure	Author
Powder bacteria 10^8 CFUs, powder, 0.3 g/l beef extract, 0.5 g peptone, 0.5g sodium chloride, ph 7-7.4, inoculation on petri agar dishes. Incubation 37 °C, 24 h, autoclave solution in conical flask to orbital shaker 150 rpm 24 h	Parashar and Gupta (2020)
cultures maintained, sub-cultured in Nutrient Agar slants. Bacterial culture was inoculated in a sterilized conical flask containing Nutrient Broth media comprising peptic digest of animal tissue (5 g/L), Sodium chloride (5 g/L), Beef extract (1.5 g/L) and Yeast extract (1.5 g/L). After inoculation, the flask was placed in a shaking incubator at 37 ◦C and 120 rpm for 24 h. The cultured growth media was mixed directly in the concrete at 5 × 10^5 cells/ml of culture media.	Bakr et al. (2023)
The culture medium was autoclaved at temperature of 110◦C, until a pressure of 1.25kg/cm^2 was achieved. The inoculated medium was incubated at a temperature of 37◦C for 48 hours and 150-250 rpm. The bacterial cell concentration was monitored using a spectrometer at OD600	Jain et al. (2023)
Bacterial cells maintained at -80 °C in 50 % (v/v) glycerol, cultured on nutrient agar plates at 30 °C for 24 h. Pure colonies transferred to sterile nutrient broth and culture incubated at 30 °C with agitation at 150 rpm for 24 h. A curing liquid for bacterial concrete was prepared. Nutrient broth for this medium (5,0 g peptone, 1,5 g bovine extract, 1,5 g yeast extract, and 5,0 g sodium chloride per litre) autoclaved and supplemented with filter-sterilized 2 % urea solution and 25 mM $CaCl_2$(NBU medium). Medium contained bacteria (Bacillus megaterium) at a concentration of 3×10^6cells/ml.	Yıldırım and Özhan (2023)

Methods of Incorporating Bacteria into Mortar

Many methods of incorporating bacteria into concrete or mortar mixes have been discussed in literature. Instead of mixing water whether suspending in mixing water or replacing mixing water with the solution containing bacteria and nutrients called vegetative inoculation (Bundur et al., 2015; Parashar & Gupta, 2020). Injections into cracks (Jongvivatsakul et al., 2019). Curing in bacterial solutions or in a supplementary solution that could contain urease or the calcium source (Schwantes-Cezario et al., 2020). Calcium sources are many; calcium nitrate, calcium acetate, calcium chloride and calcium lactate are some of the more used ones.

Because when it comes to encapsulation or what is termed sometimes as immobilization or use of carriers, many of those were studied; glass, ceramic, porous materials, nano tubes, polyurethane tubes, microcapsules, graphite nanoplatelets, lightweight aggregates, diatomaceous earth or diatomite, expanded clay.

Supplementary Cementitious Materials in MICP

Ground granulated blast furnace slag, silica fume and fly ash can be incorporated in mortar and concrete mixes to minimize the cost that the addition of the bacteria has caused (Shashank &

Nagaraja, 2022), to decrease the pH, decrease the heat of hydration, improve the density, also help with the pozzolanic effect. (Tayebani & Mostofinejad, 2019; Bhavan et al., 2017; Sadeghpour & Baradaran, 2023).

The replacement of cement by fly ash or what is called fly ash concrete has been found to support the bacterial mineralization effect on concrete in multitude of research. Sadeghpour and Baradaran (2023) used three types of bacteria; sporosarcina pasteurii, bacillus megaterium and bacillus subtilis together with replacing 20% of the cement in the mixes. This combined effect had a positive effect on increasing compressive strength and decreasing the transit time of pulse velocity. The best reduction in water absorption was achieved with bacillus subtilis and best compressive strength with bacillus megaterium at 10^5 with 39.5% increase when used with fly ash.

Pannem et al. (2023) replaced coarse aggregates with 30% fly ash aggregates and used bacillus subtilis for mineralization and healing of cracks and achieved an increase in strength of almost 61% and a healing of cracks of nearly 0.25 mm which were measured at 56 days after being induced at 28 days.

Effects of Bacteria Incorporation

The effects of bacteria is usually studied in terms of efficiency of crack heal (Qureshi & Al-Tabbaa, 2020) whether by visual inspection of length, width or area. The effect on mechanical performance, in terms of strength. The effect on density, which is always related to permeability, water absorption, sorptivity and chloride or sulfate resistance. Even though, a sacrifice in strength or strength recovery might occur, but the sealing of the path to reinforcement is much more important in terms of durability, which at that point in the life of the structure is more significant (Morsali et al., 2019).

Till 2019, the highest strength gain in microbial concrete was found to be 50% with bacillus cereus, at a concentration of 10^6 cells/ml versus a maximum water absorption decrease of 80%-85% in bacillus pasteurii (Morsali et al., 2019).

The effect of incorporating bacteria of sporosarcina pasteurii in 10^7 cells/ml in mortar samples with two different calcium sources, calcium chloride and calcium lactate on the electrical resistance and chloride permeability (Tayebani & Mostofinejad, 2019). There was a reported increase in electrical resistance and compressive strength, the best increase in compressive strength was 60% in the case of calcium chloride as a calcium source. A reduction in water absorption was observed, however better in mixes with calcium lactate that calcium chloride with 49% against 55%. There was a decrease in chloride ion penetration improving durability. The usual interactions of the bacteria and its calcite precipitation is introduced in Figure 2.

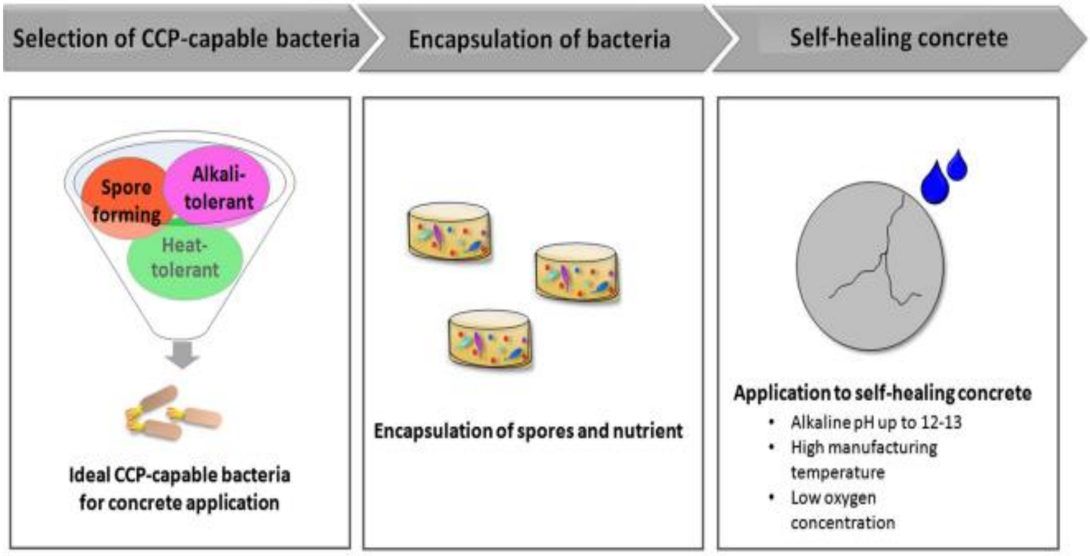

Figure 2: The inner workings of microbial-induced calcite precipitation in the concrete matrix, (Lee & Park, 2018).

Carriers/Immobilization for Bacteria/Encapsulation

Importance of Carriers in MICP

A lot of research opts for using encapsulation as a means to providing carriers for the bacteria to be in to ensure the bacteria does not fail to stay alive in the harsh inner environment of the concrete matrix. Some of which are shown in Table 2. The main key criteria to be considered when choosing a carrier, is for the carrier to be compatible with the bacteria and not compromise the mechanical characteristics of concrete as well as the strength of the carrier must be enough to handle not breaking too early but not too strength that it does not break at well when crack is formed and bacteria action is needed. Another key factor is that they must be uniformly distributed so they have even chances of being in the place of crack formation (Lee & Park, 2018).

Table 2: Review of various carriers and immobilization techniques.

Diatomite	Na-X zeolite with bacillus subtilis bacteria in different combinations	Can be options for carriers only when bacteria impregnated into them and nutrients were added to the mixing water.	Janek et al. (2022)
	Bacillus subtilis was used as self-healing agent in both mortar and concrete samples	Together they formed pellets and were mixed into the concrete as normal aggregates in some of the concrete mixes, other mixes had the bacteria solution just mixed in the mixing tap	Huynh et al. (2017)

		water. In mortar, it was added as an admixture.	
Core Shell	Bacteria spores and its nutrients in powder form	Were produced in powder form, which is the component of the core, then the core is covered with a shell made of sulfoaluminate cement, fly ash and iron sand powder in a ratio of 3:1:1	Zhang et al. (2021) Acarturk et al. (2023)
Expanded Particles	Bacillus cohnii bacteria immobilized spores in sugar-coated expanded perlite, which sometimes can be regarded as lightweight aggregates.	spores were placed in the expanded perlite particles and the nutrients and then it was coated with a protective layer, that ensured that no water permeates into the core during the mixing process, as well as keep the bacteria encapsulated till it is time for the crack healing	Jiang et al. (2020)
Biochar	Bacillus sphaericus spores immobilized in biochar	Spores immobilized in biochar with superabsorbent polymers and polypropylene fibres. promoted calcite precipitation, effectively sealing cracks wider than 700 micrometers. Incorporated fibres and superabsorbent polymers (SAPs) to enhance autogenous healing by blocking and filling cracks. However, the sealing achieved with this method was limited to cracks less than 250-500 micrometres wide.	Gupta et al. (2018) Gupta et al. (2022) Kua et al. (2019)
Lightweight Aggregates	Pre-wetted lightweight fine expanded shale aggregates as a reservoir for nutrients for the microorganism Sporosarcina pasteurii, along with a urea-yeast extract solution.	Prolonged the life of vegetative cells and improved viability without compromising strength. By inoculating the bacteria into the mortar and incorporating the reservoir for nutrients, they achieved a delayed release of nutrients, benefiting both hydration and bio-mineralization.	Bundur et al. (2017)
Air-Entrained Voids	Air-entraining agents with polyvinyl alcohol	Facilitates bacterial activity and mechanical	Chen et al. (2021)

	fibers sporosarcina pasteurii bacteria (ranging from 0 to 2 × 10^7 cells/ml)	strength recovery post-cracking.	
Biogranules	Nitrate-reducing biogranules containing varying doses of bacteria, ranging from 0.25% to 3.00% w/w cement.	Affordability for crack healing applications	Sonmez and Ercan (2022)

External Addition of Bio Solutions

Research has also been done on externally adding the microbial agent for crack sealing, Jongvivatsakul et al. (2019) artificially produced a crack in mortar, then produced a bacterial solution containing bacteria of Bacillus sphaericus group $1.8x10^{12}$ cells/ml, a yeast-urease (YU) solution along with a calcium source of calcium chloride ($CaCl_2$) was used to pour into crack that was edged by silicon glue to avoid spillage or loss of agent. They investigated for microstructure and visual observation of cracks as well as strength and water tightness. The visual inspection showed a formation of calcite in the form of vaterite that sealed crack up to 34% of area in 6 days and 85% or area at 20 days. They reported 43% recovery of strength when compared to artificially-cracked specimens that were not microbially-mineralized. However, the microbial specimens had less strength than neat concrete. Water tightness values were comparable to control specimens, which suggests improved densification again.

Curing in a bacterial solution was also studied (Yıldırım & Özhan, 2023), where some specimens incorporated the bacteria (bacillus megaterium spores) inside them and other were cured in water containing bacteria, samples cured in bacteria had a reduction in their water absorption levels as the calcite was precipitated by the bacteria on the surface of the concrete.

Study of Densification Effect

Many research was aiming at densifying the concrete mixes and filling up the voids as opposed to specifically healing cracks. As reducing the air voids would result in better mechanical performance and increased durability due to decreased permeability (Acaturk et al., 2023).

Pasharashar and Gupta (2020) used bacillus bacteria of the bacillus megaterium species to fill voids in the concrete matrix, the bacteria was used in quantity of 10^8 CFU (colony-forming unit), as they aimed to densify the mix and eliminate the voids that affect the strength of concrete against shrinkage and settlement. They reported an increase in all mechanical strength, compressive, tensile and flexural in percentages between 9 and 12% when compared to control.

Another type of the bacillus family which is bacillus amyloliquefaciens, which is a soil bacteria very similar to bacillus subtilis the type that is chosen for the present study. The bacteria was used in $2.5×10^7$ cells/mL. The process of pre-loading and unloading was utilized in the study. They measured both compressive strength and sorptivity of both cubes under both loading conditions, apart from concluding that this type of bacteria is capable of precipitating calcite but also the presence of it generally decreases sorptivity due to the densification and also the sorptivity has an increasing trend with age of curing as cracks are healed and mitigated. When compared to conventional cubes that the sorptivity is generally less and decreases with age. The unloaded specimens had better sorptivity but lower compressive strength that preloaded cubes. Many research was conducted on sporosarcina pasteurii in self-healing or bio-concrete and many factors and effects were investigated. In the study of Bundur et al. (2015), hydration kinetics along with compressive strength was studied. They specifically opted for vegetative bacteria, not in spore forms, they used a urea-yeast extract as medium for said bacteria. There samples were categorized by some having only the medium, some having vegetative bacteria along with the medium mix and the last category of mixes had killed bacteria with the medium, the concept behind the last mix type is to investigate whether killed bacteria can still have calcite producing activity.

Most studies focus on healing within 28 days making encapsulation less of an issue. As it was proved that a percentage of bacteria remain viable even after 11 months of casting (Amiri & Bundur, 2018), also encapsulation might be unnecessary if bacteria is able to produce endospores self-protecting itself, in which case bacteria can stay viable for long periods of time as well (Bundur et al., 2015).

A study on sporosarcina pasteurii, Bundur (2017a) in terms of porosity reduction and its longer-viability in vegetative inoculation state without encapsulation and they found that it could remain viable till 330 days and 48% of them were in vegetative state, and they reported better viability in mortar than in paste, which is a favourable result as mortar is more representative of the actual dynamics of a concrete mix. Not to mention that in fact adding this bacteria did decrease porosity and increase strength regain.

The nutrient components, especially, yeast extract contain sugary ingredients that causes retardation in the hydration kinetics. Which was obvious in all mixes, the early strength can be lower in mixes containing nutrients because of that. However, it tends to increase with time and exceed conventional mortar. Some calcite precipitation was noticed in mixes containing dead cells. Significant production was observed in mixes containing vegetative bacteria that they concluded there was no need for encapsulation for shorter term effects.

Nutrient medium could have yeast extract and urea, however yeast extract has been found to be responsible for retarding the hydration and increasing setting time not to mention the added cost, Amiri and Bundur (2018) replaced this carbon source with corn-steep liquor. This ensured a better setting without compromising the compressive strength and the bio mineralization.

As yeast extract mediums were reported to cause retardation in the setting time. Search for alternatives has been the main aim of multiple research. In Amiri and Bundur (2018), they replaced the urea-yeast extract (UYE) with a urea-corn steep liquor for sporosarcina pasteurii as well which proved to be a suitable alternative, as it has not affected the bacterial viability or even the calcite precipitation. It also did not compromise the setting time or compressive strength when compared to neat samples.

Long-Term Investigation

Authors have reported lack of research in the fields of long-term investigation of what bacterial concrete is. What happens at later stages, especially on a biological level, germination, and processes other than the self-healing (Lee & Park, 2018).

Other problems with durability and mechanical performance assessment is discussed in by Jakubovskis et al. (2020), which are the fact that all the tests conducted on those criteria are very laboratory based and are not representative of real life environment and real-life progress and after-crack behavior. Thus, tests are to be conducted in a way to test crack healing under free-thaw conditions, marine conditions and sustained loads. Those tests must be made to simulate the effect of those conditions correctly. Also test setups where mechanical performance and durability can be tested and estimated simultaneously could reduce the scatter between the results of those two categories separated. Another limitation discussed was that testing must happen or reinforced concrete more often as it is more representative of real life progression of cracks.

A study on reinforced concrete was done by Ling and Qian (2017) where they introduced bacteria of the type Paenibacillus mucilaginosus to reinforced specimens to test the efficiency of crack healing and reduction of chloride transmission to avoid corrosion. Electro-chemical test along with visual examination of cracks surface, weight-loss ratio of reinforcements and chloride ion content were all tested. Most importantly, the method of electro-migration was used to accelerate the transmission of chloride. The results showed that the degree of corrosion decreased when cracks were healed. Visual examination also showed lower weight-loss ratio of reinforcements and the chloride content was lower.

Economic Feasibility

Autonomous self-healing by all means is considered be the most cost efficient and easiest in the implementation aspect as it is compatible with the concrete matrix and a truly-engineered autonomous self-healing can be 10 times more costly than ordinary concrete. (Jakobovskis et al., 2020). Amran et al. (2022) saw potential for bio-based structures that are capable of self-healing to become a cost-efficient option in the future especially when compared to maintenance costs and longer service life, same statements were made by Zhang and Qian (2022) and urged the need for efforts in lowering the cost of self-healing concrete by finding cheaper options for bacteria and their nutrients as well as for the calcium source needed for the bacteria to produce calcite. The current cost of this technology is around USD 33–44/m^2, which means it could be implemented in special cases when corrosion is at hand.

Conclusion

One of the most innovative new approaches to concrete and mortar preservation is the application of self-healing to induce crack sealing. Self-healing, especially the method incorporating microbially-induced precipitation of calcite that aids with the healing of cracks has proved to be a technique that is compatible with the concrete matrix which aids in the attempt to achieve denser, stronger and more durable structures. Hence, the cost of repair and maintenance can be drastically reduced. The investigation long-term implications and effect of using bacteria in concrete structures remains hopeful for more meticulous efforts in the near future for better comprehension of the ways to enhance it and prevent any negative effects. Apart from all of this, the cost remains a challenge as the bacteria and their needed-nutrients are not of cheap cost. Enhancing the sustainability of such technique will definitely be an achievement in the construction sector.

References

Acarturk, B. C., Sandalci, I., Hull, N. M., Bundur, Z. B., & Burris, L. E. (2023). Calcium sulfoaluminate cement and supplementary cementitious materials-containing binders in self-healing systems. *Cement and Concrete Composites*, *141*, 105115.

Acarturk, B. C., Straathof, J., Liu, Y., Hull, N., Bundur, Z. B., & Burris, L. E. (2023). Novelty in bacteria source production and concrete binders in self-healing cementitious samples. *Proceedings of MATEC Web of Conferences,* p. 02006.

Amiri, A., & Bundur, Z. B. (2018). Use of corn-steep liquor as an alternative carbon source for biomineralization in cement-based materials and its impact on performance. *Construction and Building Materials*, *165*, 655-662.

Amran, M., Onaizi, A. M., Fediuk, R., Vatin, N. I., Muhammad Rashid, R. S., Abdelgader, H., & Ozbakkaloglu, T. (2022). Self-healing concrete as a prospective construction material: a review. *Materials*, *15*(9), 3214.

Bakr, M. A., Singh, B. K., Deifalla, A. F., Pandey, S., Hussain, A., Ragab, A. E., & Hasnain, S. M. (2023). Assessment of the mechanical and durability characteristics of bio-mineralized Bacillus subtilis self-healing concrete blended with hydrated lime and brick powder. *Case Studies in Construction Materials*, e02672.

Başaran Bundur, Z., Bae, S., Kirisits, M. J., & Ferron, R. D. (2017a). Biomineralization in self-healing cement-based materials: investigating the temporal evolution of microbial metabolic state and material porosity. *Journal of Materials in Civil Engineering*, *29*(8), 04017079.

Bundur, Z. B., Amiri, A., Ersan, Y. C., Boon, N., & De Belie, N. (2017b). Impact of air entraining admixtures on biogenic calcium carbonate precipitation and bacterial viability. *Cement and Concrete Research*, *98*, 44-49.

Bundur, Z. B., Kirisits, M. J., & Ferron, R. D. (2015). Biomineralized cement-based materials: Impact of inoculating vegetative bacterial cells on hydration and strength. *Cement and Concrete Research*, *67*, 237-245.

Bundur, Z. B., Kirisits, M. J., & Ferron, R. D. (2017c). Use of pre-wetted lightweight fine expanded shale aggregates as internal nutrient reservoirs for microorganisms in bio-mineralized mortar. *Cement and Concrete Composites*, *84*, 167-174.

Chen, B., Sun, W., Sun, X., Cui, C., Lai, J., Wang, Y., & Feng, J. (2021). Crack sealing evaluation of self-healing mortar with Sporosarcina pasteurii: Influence of bacterial concentration and air-entraining agent. *Process Biochemistry*, *107*, 100-111.

Gupta, S., Kua, H. W., & Dai Pang, S. (2018). Healing cement mortar by immobilization of bacteria in biochar: An integrated approach of self-healing and carbon sequestration. *Cement and Concrete Composites*, *86*, 238-254.

Gupta, S. (2022). Comparison of improved autogenous and bio-based self-healing techniques in fiber-reinforced mortar: effect of bacteria incorporation strategy and fiber hybridization. *Journal of Building Engineering*, *45*, 103607.

Huynh, N. N. T., Phuong, N. M., Toan, N. P. A., & Son, N. K. (2017). Bacillus subtilis HU58 Immobilized in micropores of diatomite for using in self-healing concrete. *Procedia Engineering*, *171*, 598-605.

Jakubovskis, R., Jankutė, A., Urbonavičius, J., & Gribniak, V. (2020). Analysis of mechanical performance and durability of self-healing biological concrete. *Construction and Building Materials*, *260*, 119822.

Janek, M., Fronczyk, J., Pyzik, A., Szeląg, M., Panek, R., & Franus, W. (2022). Diatomite and Na-X zeolite as carriers for bacteria in self-healing cementitious mortars. *Construction and Building Materials*, *343*, 128103.

Jiang, L., Jia, G., Jiang, C., & Li, Z. (2020). Sugar-coated expanded perlite as a bacterial carrier for crack-healing concrete applications. *Construction and Building Materials*, *232*, 117222.

Jongvivatsakul, P., Janprasit, K., Nuaklong, P., Pungrasmi, W., & Likitlersuang, S. (2019). Investigation of the crack healing performance in mortar using microbially induced calcium carbonate precipitation (MICP) method. *Construction and Building Materials*, *212*, 737-744.

Kua, H. W., Gupta, S., Aday, A. N., & Srubar III, W. V. (2019). Biochar-immobilized bacteria and superabsorbent polymers enable self-healing of fiber-reinforced concrete after multiple damage cycles. *Cement and Concrete Composites*, *100*, 35-52.

Lee, Y. S., & Park, W. (2018). Current challenges and future directions for bacterial self-healing concrete. *Applied Microbiology and Biotechnology*, *102*, 3059-3070.

Ling, H., & Qian, C. (2017). Effects of self-healing cracks in bacterial concrete on the transmission of chloride during electromigration. *Construction and Building Materials*, *144*, 406-411.

Morsali, S., Yucel Isildar, G., Hamed Zargari, Z., & Tahni, A. (2019). The application of bacteria as a main factor in self-healing concrete technology. *Journal of Building Pathology and Rehabilitation*, *4*, 1-6.

Özhan, H. B., & Yildirim, M. (2020). Effects of acid and high-temperature treatments on durability of bacterial concrete. *Uludağ Üniversitesi Mühendislik Fakültesi Dergisi*, *25*(3), 1421-1430.

Pannem, R. M. R., Bashaveni, B., & Kalaiselvan, S. (2023). The effect of fly ash aggregates on the self-healing capacity of bacterial concrete. *Ain Shams Engineering Journal*, 102261.

Parashar, A. K., & Gupta, A. (2021, April). Experimental study of the effect of bacillus megaterium bacteria on cement concrete. *IOP Conference Series: Materials Science and Engineering*, *1116*(1), 012168.

Qureshi, T., & Al-Tabbaa, A. (2020). Self-healing concrete and cementitious materials. *Advanced Functional Materials*, 191-213.

Sadeghpour, M., & Baradaran, M. (2023). Effect of bacteria on the self-healing ability of fly ash concrete. *Construction and Building Materials*, *364*, 129956.

Schwantes-Cezario, N., Camargo, G. S. F. N., do Couto, A. F., Porto, M. F., Cremasco, L. V., Andrello, A. C., & Toralles, B. M. (2020). Mortars with the addition of bacterial spores: evaluation of porosity using different test methods. *Journal of Building Engineering*, *30*, 101235.

Shashank, B. S., & Nagaraja, P. S. (2022). Fracture behavior study of self-healing bacterial concrete. *Materials Today: Proceedings*, *60*, 267-274.

Sonmez, M., & Erşan, Y. Ç. (2022). Production and compatibility assessment of denitrifying biogranules tailored for self-healing concrete applications. *Cement and Concrete Composites*, *126*, 104344.

Tayebani, B., & Mostofinejad, D. (2019). Self-healing bacterial mortar with improved chloride permeability and electrical resistance. *Construction and Building Materials*, *208*, 75-86.

Yıldırım, M., & Özhan, H. B. (2023). Effect of bacterial curing and bacterial additive on concrete properties: DOI registering. *Advances in Civil and Architectural Engineering*, *14*(27), 32-43.

Zhang, X., Jin, Z., Li, M., & Qian, C. (2021). Effects of carrier on the performance of bacteria-based self-healing concrete. *Construction and Building Materials*, *305*, 124771.

Zhang, X., & Qian, C. (2022). Engineering application of microbial self-healing concrete in lock channel wall. *Marine Georesources & Geotechnology*, *40*(1), 96-103.

Evaluation of the Lean Construction System in Terms of Ecological Architecture

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Abstract

Although the construction sector is one of the main sectors in directing the world economy, it embodies many problems such as waste, destruction and cost loss in terms of environmental impacts. In this context, ecological architecture has emerged with the approach of "environmentally sensitive construction" despite the scarcity indicators caused by environmental destruction and the increase in resource use, and has become one of the priority targets of today's construction sector. Lean construction, on the other hand, exists as the reflection of lean production, which was created in the mid-20th century based on the success and experience of the Toyota automotive system in production, in the construction sector. The lean construction system, which was produced as an alternative to traditional construction systems, is a system focused on reducing resource waste and increasing efficiency and quality by optimizing business processes. Within the scope of the study, the lean construction system was analyzed and examined through studies. In the light of the information obtained, the types of waste in lean construction were evaluated in terms of ecological architecture criteria. As a result, it has been reached that the types of waste in the lean construction system have emerged as a result of not taking into account today's ecological criteria. In this context, it is possible to say that the lean construction system and ecological architecture criteria interact with each other and if their processes are integrated, sustainability goals will be positively affected.

Keywords: *ecological architecture, project management, sustainability, lean construction.*

Introduction

Ecological architecture and lean construction concepts play an important role in the construction industry today. Ecological architecture aims at the philosophy of harmony with nature and lean construction aims at the philosophy of continuous improvement, but both approaches are based on the concept of waste (Tönük, 2001; Ohno & Bodek, 1988). For this reason, it is aimed to create a focal point for the development of these two concepts on a common ground by examining the relationship between ecological architecture and lean construction. In this context, the concepts of ecological architecture and lean construction are first analyzed.

Ecology in architecture is an architectural philosophy based on harmony with nature that has emerged as a solution to many environmental, social and economic problems caused by the increase in population and technology (Tönük, 2001; Crowther, 1992). Ecological architecture is based on designs that are compatible with nature and climatic/regional conditions. Ecological architecture supports phenomena such as the mutual benefit of the environment and people, recycling, reuse, the use of ecological materials, smart building systems, and the use of renewable energy in buildings. The aim of ecological approaches is to produce solutions that will not harm the natural balance by using existing resources without conflicting with nature (Çetin, 2010). At the point of associating ecological design with buildings in architecture, ecological design criteria come into play (Roaf, 2003). In this context, ecological architectural design criteria were developed in this study based on the definitions of ecological architecture previously made in the literature.

Lean production in architecture comes to life with the concept of lean construction. Lean construction is a project delivery method developed to improve the time, quality and cost triangle with lean production principles; to ensure collaboration between teams, to reduce waste and to increase stakeholder value (Ohno & Bodek, 1988; LCI, 2023). Although the concept of lean manufacturing has a long history, its development has been slow in the construction industry due to the fact that each project is unique and stakeholders do not know the importance of lean to the same extent (Warcup, 2015). In addition, lean construction has proven to be a successful production model in companies where the lean production model can be applied (Merker, 2018). The main purpose of lean construction is to reduce waste and a total of 9 types of waste have been identified.

In this study; The examined ecological architecture and lean construction concepts were based on the criteria determined in the literature. These determined criteria and both concepts were compared and analyzed. In the study, the occurrence of waste types in the lean construction system as a result of ignoring today's ecological criteria was examined. In this context, it is possible to say that sustainability targets will be positively affected if the lean construction system and ecological architecture criteria interact with each other and their processes are integrated.

Material and Method

At the end of the literature review in the study, information about concepts about ecological architectural design was given. This has been deemed important in determining ecological architectural design criteria. The concepts that explain ecological architecture in the definitions are shorthand for ecological architectural design.

In another title of the study, lean production and waste, which is the main philosophy of lean production, are discussed. As a result of the study, the relationship between ecological architectural design criteria and the 9 basic waste types of lean production was revealed and the compliance of lean production with today's ecological design criteria was questioned.

Ecological Architecture

Ecological architecture has been put forward to take measures against increasing environmental, social and economic problems and consumption habits in the construction sector (Belek & Yamaçlı, 2023; Steadman, 1998). Ecological architecture is an approach to architecture that is sensitive to people and the environment, minimizes environmental damage, adapts to climatic conditions and topography, building materials are compatible with nature, local and recyclable, and energy conservation or recovery is ensured (Tönük, 2001; Wachberger & Wachberger 1988; Uffelen, 2009; Aytıs & Polatkan, 2009).

The concept of ecological architectural design has been explained in different ways in the literature. In the definitions made, ecological architecture is an approach to architecture that aims for energy efficiency and can produce its own energy, where natural lighting and recycling are important, effective insulation and environmentally friendly architecture (Hasol, 2014). Kısa Ovalı (2009) states in his study that Drings (1990) and Hegger (1997) explain ecological architecture as being in harmony with nature with all the processes of the building throughout the building life cycle and not harming the environment (Kısa Ovalı, 2009). Again Kısa Ovalı (2009) defines ecological architecture as "a phenomenon that is sensitive to human beings, addresses the physical environment from a broad perspective, and all inputs and outputs are compatible with the ecological system throughout the building life cycle (Kısa Ovalı, 2009). Wachberger and Wachberger (1988), on the other hand, consider ecological architecture as the understanding of constructing buildings that are compatible with topography and local climatic conditions, using renewable energy sources and respecting energy resources (Wachberger, 1988).

Ecological architecture is the provision of architecture in harmony with nature in the formation of an environment. Recycling is essential in ecological architecture (Tönük, 2001). Uffelen (2009) defined ecological architecture as the protection of natural resources and social welfare by minimizing environmental impacts (Uffelen, 2009). Türkmenoğlu Bayraktar (2011) and Alparslan et al. (2009) explained ecological architecture as the use of recyclable, healthy and natural materials in the design of buildings and settlements, with emphasis on the protection of natural environments (Türkmenoğlu Bayraktar, 2011; Alparslan et al. 2009). According to Kleiner (2003), ecological architecture is the construction of energy-conserving buildings where green is preserved and improved (Kleiner, 1995). Crowther (1992) emphasized that the natural form of the land should be preserved (Crowther, 1992); Roaf (2003) emphasized that buildings should be considered as a part of the ecosystem (Roaf, 2003). Based on these definitions, some criteria for ecological architecture have been determined.

These criteria are; harmony with nature, harmony with topography, use of renewable energy, conservation of natural resources, social welfare, recyclability, reuse, conservation of natural resources, use of healthy and durable materials, easily maintainable building/material, economical building/material, human sensitive building, energy conservation building, conservation of green and avoiding difficult applications such as excavation and filling by preserving the natural form of the land. These ecological criteria identified within the scope of the study are grouped and explained (Table 1).

Table 1. Criteria of ecological architecture.

Types	Content
Site/Land	Site selection (Ecology, excavation) Adaptation to topography
Building environment	Protecting green Preservation of natural landform Adaptation to surrounding buildings
Building	Orientation Facade design (transparent or blind surfaces) Roof design
Ensuring social welfare	Respect for human beings Respect for nature Affordability Health, Education, Job opportunities, Social security, Social inclusion Management
Material	Recyclable Easy to maintain Reusable Durable Local Economic Easy to process Healthy
Protection/Acquisition	Energy conservation/energy efficient building Use of renewable energy Protection of natural resources Minimizing resource consumption

Lean Production

Lean manufacturing; It emerged with the work of Japanese Industrial Engineer Taichi Ohno after World War II. Lean production is a systematic production method and management philosophy derived from the Toyota Production System (TPS) and developed to eliminate waste, continuous improvement and increase efficiency (Crainer, 2002; Liker, 2004; Akers, 2016; Amaro et al., 2019). Lean production aims to ensure that there is a significant difference between the output and input of each process in the process and to prevent waste by identifying the ones that do not have added value among these processes (Amaro et al., 2019). In addition to this, the positive aspects of the lean philosophy are that it is high quality and customer-oriented with fewer resources and stocks, with a holistic approach in which all parts of the system are considered together in lean production (Katayama & Bennett, 1996). There are 6 basic principles of lean management approach in production (Table 2). These principles are the main factors in reducing waste and increasing productivity (Womack & Jones, 1996; Woehrle & Abou-Shady, 2010; LCI, 2023).

Table 2. 6 basic principles of lean management.

Principles	Explanation
Respect for people	It is the first step of the lean production philosophy. It expresses respect for both the people and partners working together and the customers. Operations that do not add value to the customer are considered waste and are expected to be eliminated (Womack & Jones, 1996).
Optimize the Whole	They are studies on the planning of projects as a whole (LCI, 2023).
Eliminate Waste	It refers to identifying and eliminating the types of waste that arise in projects (LCI, 2023).
Focus on Process & Flow	Service control and continuous product flow by avoiding delays between value-adding transaction times (LCI, 2023).
Generation of Value	Taking measures against transactions that may cause waste in the process of delivering the service/product to the customer (Woehrle & Abou-Shady, 2010).
Continuous Improvement	Ensuring the perfection and continuous improvement of the product/service (LCI, 2023).

The success and benefits of the lean production system against its competitors in the automotive system have led to the spread of lean policies in other sectors. One of these sectors is the construction sector with its important place in the national economy. In the research conducted, the magnitude of efficiency loss and waste in the construction sector is revealed. In this respect, the concept of lean construction has emerged with the reflection of lean production on the construction sector. The concept of lean construction was used at the International Group of Lean Construction (IGLC) conference in 1993. The conference emphasized the need to do a better job in construction project management in the triangle of time, quality and cost and to adopt lean manufacturing principles (Ohno & Bodek, 1988). Lean Construction Institute (2012) defines lean construction as a project delivery method that uses lean production methods to optimize stakeholder value and reduce waste by emphasizing collaboration between teams. The goal of lean construction is to increase innovation, productivity and profit in the construction industry (LCI, 2012).

The first example of the application of lean construction is the Empire State Building, which predates the emergence of the "lean concept" by about 50 years. The building had to be completed by a certain date, and before its construction, designer decisions were taken, its statics were determined, permits were obtained and the existing buildings in the area were demolished and it was built in 20 months as predetermined (Ghosh & Robson, 2014). However, despite the long history of lean construction, the development of the concept of "lean" in the construction industry has been slow. It is possible to say that the main reason for this situation is that each project in the construction sector is unique and there are multiple stakeholders and not all stakeholders know the importance of lean to the same extent (Warcup, 2015). In addition, lean construction has proven to be a successful production model in companies where the lean production model can be applied. According to the results of a survey conducted by McGraw Hill's Construction Research and Analytics (2013) on the implementation of lean construction to contractors, the study found that lean construction leads to higher quality, higher productivity, greater customer satisfaction, lower costs, shorter project duration, better reliability performance, and increased profits (Merker, 2018).

In traditional projects in the construction industry, many of the conditions set before the work are not met. For example, time and cost overruns, customer and stakeholder dissatisfaction, and work accidents are some of these conditions. In this respect, the final planning system aims to identify the work flow process between the parties and potential problems and take measures to achieve more reliable results. The main issue of lean production is to eliminate waste and eight main waste topics are mentioned. These are; unnecessary transportation, waiting time, overproduction, defects, unnecessary storage, wasted motion, overprocessing (Ohno & Bodek, 1988) and unused talent (Table 3) (Akers, 2016). In this context, the wastage classes identified in lean production were also addressed in the construction sector, but a ninth wastage class called "designing a product that does not respond to customer needs" was introduced in the studies (Womack & Jones; 1996). It is important for the lean construction practice to identify and eliminate the given 9 wastes at management, employee and personal level.

Table 3. Types of waste in lean construction.

Type	Content
Unnecessary Transportation	It is the type of waste that occurs during the transportation of materials, raw materials and productions to be used in building design (Rich et al., 2006).
Waiting Time	It occurs as a result of obstacles in the active progress of the production process. This is a type of waste caused by activities such as manufacturing errors, machine breakdowns, work accidents, inefficient and unplanned work (Yorke & Bodek, 2005).
Defects	Waste arising from defective products and process design in cases requiring post-production maintenance (Yorke & Bodek, 2005).
Overproduction	It occurs as a result of making more than the required amount of the product. Unnecessary warehousing process leads to consequences such as labor force utilization, cost overruns, pollution, unnecessary transportation, wasted movement (Liker, 2004).
Unnecessary Storage	It is the situation of overstocking the product as a result of producing more than desired (Liker, 2004).
Wasted Motion	It includes additional movements that occur in cases such as overproduction, defective production, unnecessary transportation of the product, unplanned movements (Bodek, 2004).
Over Processing	Unnecessary processing such as processing more than necessary to meet customer needs, finding the wrong parts, selecting materials that cannot be easily processed, etc. (Bodek, 2004).
Unused talent	Underutilization of people's talents, skills and knowledge (Akers, 2016).
Designing a Product that Does Not Respond to Customer Needs	It includes processes and activities that do not add value to the customer and do not define the customer's needs (Womack & Jones; 1996).

Findings

In the study, the criteria of ecological architecture and the types of waste in lean construction were tried to be compared. Accordingly, the types of waste that will occur if ecological architecture criteria are not met have been systematized (Table 4).

Table 4. Mutual evaluation of ecological architectural design criteria and lean construction waste types.

Ecological architectural design criteria		Lean construction waste types
Site/Land	Site selection (Ecology, excavation) Adaptation to topography	Waiting Time Wasted Motion Over Processing
Building environment	Protecting green Preservation of natural landform Adaptation to surrounding buildings	Waiting Time Wasted Motion Designing a Product that Does Not Respond to Customer Needs
Building	Orientation Facade design (transparent or blind surfaces) Roof design	Designing a Product that Does Not Respond to Customer Needs Wasted Motion Unused talent Overproduction
Ensuring social welfare	Respect for human beings Respect for nature Affordability Health, Education, Job opportunities, Social security, Social inclusion Management	Unnecessary Transportation Waiting Time Defects Overproduction, Unnecessary Storage Wasted Motion Over Processing Unused talent Designing a Product that Does Not Respond to Customer Needs
Material	Recyclable Easy to maintain Reusable Durable Local Economic Easy to process Healthy	Unnecessary Transportation Waiting Time Defects Wasted Motion Over Processing Designing a Product that Does Not Respond to Customer Needs
Protection/Acquisition	Energy conservation/energy efficient building Use of renewable energy Protection of natural resources Minimizing resource consumption	Unnecessary Storage Overproduction

Land selection is important in building design. First of all, the ecological value of the land must be low. For example, lands such as forests, wetlands, and natural habitat areas are lands with high ecological value. Instead of these lands, areas with low ecological value such as agricultural areas and urbanization areas should be preferred (Crowther, 1992). The building design to be built must be compatible with the land topography. If this condition is not met, unnecessary filling and excavation operations are carried out, and as a result, the waiting time of the structure increases with wasted movements and excessive processing.

The next important criterion in building design is the immediate surroundings of the building. Green areas in the immediate vicinity of the building should be protected, the natural land form should not be distorted and the city's silhouette should not be damaged. In this respect, approaches focused on protection and harmony in the immediate surroundings of the targeted building in ecological architecture are compatible with the lean construction approach by reducing overproduction and wasted movements in lean production and taking into account customer needs within the framework of respect for people.

Another factor that affects the ecological status of the building is the building design. Orienting the building according to wind and sun conditions, making transparent/blind designs in façade design, choosing roof slopes and materials sensitive to climate, and determining building openings are important contents for ecological architecture. As a result of designing these criteria in accordance with climatic and regional data, customer needs are met according to lean construction, and there is no need for repetitive and wasted movements. Adapting to climatic data in ecological architecture is the result of using the genius of designers, managers and other collaborators, which is one of the requirements of lean construction. Another important issue in providing ecological architecture is material. When choosing materials, it is important to choose recyclable, reusable, easy-to-maintain, local, durable, easily processable and healthy materials. If the material selection, which is essential in ecological architecture, is not made correctly, consequences such as unnecessary transportation/transportation time in lean construction, defects that may arise during maintenance, unnecessary movement during processing, excessive processing, product design that does not meet customer needs, and unnecessary storage operations as a result of purchasing more material than necessary. is likely to be born.

The concept of ecological architecture and conservation are considered together. Using renewable energy resources in the building, protecting natural resources, and reducing resource consumption are important for an energy-saving/saving structure. With the philosophy of protection and gain in ecological architecture, unnecessary movements in the building and other unnecessary activities caused by these movements are prevented, and in this respect, it is compatible with lean production. Social welfare must be ensured in building design. Respect for people and nature is the first step in ensuring social welfare and in the concept of management. In addition, economy, health, education, job opportunities, social security and social participation are also indicators of social welfare. In this respect, social welfare addresses the whole rather than the parts in the construction sector, and if social welfare is ignored, all types of waste are expected to occur.

Results

The concepts of ecology and lean production have been discussed in different ways for decades, but the compatibility of their basic principles has been ignored. The basis of both approaches is waste generation. In this regard, there are some criteria in ecological architecture. While an approach to harmony with nature is demonstrated with these criteria, efforts are also made to eliminate waste with lean construction principles. In this regard, the criteria of ecological architecture and the waste types of lean construction were tried to be analyzed mutually. In the study, it was found that waste was created as a result of ignoring today's ecological criteria. In this context, it is possible to say that the lean construction system and ecological architecture criteria interact with each other and that sustainability targets will be positively affected if their processes are integrated with each other. It is hoped that the study will contribute to the field and guide future studies.

References

Akers, P. (2016). *2 Second Lean: How to Grow People and Build a Lean Culture*. Washington: FastCap Press

Alparslan, B., Gültekin, AB, & Belgin Dikmen, Ç. (2009). Investigation of ecological building designs within the scope of solar houses in Turkey. *5th International Advanced Technologies Symposium (IATS'09)*, Karabük.

Amaro, P., Alves, A. C., & Sousa, R. M. (2019). Lean thinking: a transversal and global management philosophy to achieve sustainability benefits. *Lean Engineering for Global Development*, 1-31.

Aytıs, S., & Polatkan, I. (2009). Ecological Architecture Concept and Basic Principles, *International Ecological Architecture and Planning Symposium*, Ankara.

Belek, A. N., & Yamaçlı, R. (2023). Sustainable Design Criteria and Evaluation Process of Ecological Buildings. *Architecture and Life*, 8(2), 529-550.

Bodek, N. (2004). Kaikaku: *The Power and Magic of Lean: A Study in Knowledge Transfer*.

Crainer, S. (2002). *The ultimate business library: The greatest books that made management*. (3rd ed.). Oxford: Capstone.

Crowther, R. L. (1992). *Ecological Architecture*, Boston: Butterworth Architecture.

Çetin, S. (2010). Ecological Reflections of Traditional Housing Architecture: Burdur Example. *5th National Roof and Facade Symposium*.

Hasol, D. (2014). Encyclopedic Dictionary of Architecture.

Ghosh, S. & Robson K. F. (2014). Analyzing the Empire State Building Project from the Perspective of Lean Project Delivery System. *50th Annual International Conference Proceedings*.

Katayama, H. & Bennett, D. (1996). Lean Production in a Changing Competitive World: A Japanese Perspective, *International Journal of Operations & Production Management*, 16(2), 8-23.

Kısa Ovalı, P. (2009). Creation of the Systematics of Ecological Design Criteria in the Context of the Climatic Regions of Turkey "Sampling in the Settlement of Kayakoy", Trakya University, *Institute of Natural Sciences*, Doctoral Thesis.

Klenier, H. (1995). *Ökologische Architektur-Ein Wettbwerb*, (Callwey Verlag, Münnhen, 8.

Liker, J. (2004). *The Toyota way: 14 management principles from the world's greatest manufacturer.* (1st ed.). New York, NY: McGraw-Hill Education.

Merker, D. J. (2018). Lean Construction Implementation: Case Study.

Ohno, T., & Bodek, N. (1988). *Toyota Production System: Beyond Large-Scale Production*. (1st.ed.). Cambridge, MA: Productivity Press.

Rich, N., Bateman, N. & Esain, A. (2006). *Lean Evolution: Lessons from the Workplace.* New Manufacturer. New York, McGraw-Hill.

Roaf, S. (2003). Ecohouse 2; *A Design Guide*, (Architectural Press), London, 1-273.

Steadman, P. (1998) *Energy, Environment and Building Cambridge*, Cambridge University Press.

Tönük, S. (2001). *Ecology in Building Design*. Yildiz Technical University Printing and Publication Center Printing House, İstanbul.

Türkmenoğlu Bayraktar, N. (2011). Ecological standards in traditional architecture in the Context of Sustainable Architecture. *Güney Architecture*, 6, 19-22.

Uffelen, C. V. (2009). Ecological Architecture. *Architecture in Focus Series*. Braun Publishing.

Yorke, C. & Bodek, N. (2005). *All You Gotta Do Is Ask*. PCS Press.

Wachberger, M., Wachberger, H., (1988). Solar and Residential-Building with Solar, Passive Solar Energy Use, *E+P Residential Magazine*, Yaprak Bookstore, Ankara,

Warcup, R. (2015). *Successful Paths to Becoming a Lean Organization in the Construction Industry*. ProQuest Dissertations & Theses Global.

Woehrle S. L., Abou- Shady L. (2010). Using Dynamic Value Stream Mapping and Lean Accounting Box Scores to Support Lean Implementation. *American Journal of Business Education*. 3(8), 67-75.

Warcup, R. (2015). *Successful Paths to Becoming a Lean Organization in the Construction Industry*. ProQuest Dissertations & Theses Global.

Womack, J. & Jones, D. T. (1996). *Lean Thinking: Banish Waste and Create Wealth in Your Corporation*, Free Press, New York.

Integration of Lean Project Delivery and Industry 4.0 in Construction Sector

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Abstract

With the globalizing world, the need for industrial efficiency management has emerged in parallel with the increase in waste in production and the decrease in productivity. Sectors that have adopted the Lean Project Delivery System (LPDS), a solution tool that responds to this need, have focused on increasing the efficiency of the resulting product by creating a reliable workflow, eliminating all kinds of waste and providing faster product management, and successful results have been achieved. The construction sector, one of these sectors, has adapted LPDS to its own structure. Similarly, with increasing and differentiating needs, technologies defined as Industry 4.0 technologies have taken their place in the construction sector, as in many other sectors. At the same time, developing technology has also developed the understanding of lean production and different technological applications have become an important tool in achieving the goals of the lean production process. However, this system, which has recently been implemented in the construction sector, has not yet developed its association with technology sufficiently. The aim of this study is to highlight the importance of using Industry 4.0 technologies that will contribute to achieving the goals of lean thinking, which forms the basis of the developing LPDS in the construction sector. It is expected that the results of the study will contribute to research on the sector's development by raising awareness about the integration of LPDS and Industry 4.0 technologies.

Keywords: *construction sector, industry 4.0, lean construction, lean project delivery system, technology.*

Introduction

The economic crises experienced by the world economy led to a slowdown in productivity in the manufacturing sector, which in turn led to an increase in inflation and unemployment. This economic crisis has significantly increased competition in international markets (Duman, 2011). At the same time, customers in the market demand products of high quality, in the shortest time and at low cost, and firms that meet these demands can direct the market. Faced with competitive pressures, countries today have realized that traditional production systems are not sufficient to realize the strategic goals of firms and have started to search for new ones. The concept of lean production emerged as a solution to this need.

Lean production, which increases efficiency and performance in production processes, was introduced at Toyota, a Japanese automotive company. Lean production aims to establish a dependable workflow by eliminating various forms of waste, enabling the production of goods in minimal time, at the lowest feasible cost, and with the highest quality. The success of lean principles, which have also found application in the construction sector, in production and the benefits arising from their use are one of the main motivations for adopting lean principles in the sector (Toker, 2022). The Lean Project Delivery System (LPDS), which constitutes the delivery system of lean production, realizes project delivery in the least possible cost and time by focusing on user demands. While ensuring this situation, it identifies and eliminates every activity that has no value in the construction process. Traditional Project Delivery Systems (TPDS), on the other hand, try to identify the activities that cause deviations after all work items are realized (Kömürcü, 2007).

On the other hand, the development and use of smart and digital technologies has led to a transformation in different industries and business areas, particularly in the manufacturing sector, in the last decade (Karal, 2019), and this transformation is defined as Industry 4.0. The production sector is also affected by the development and transformation created by Industry 4.0.

Although the construction sector strives to benefit from the process called "Construction 4.0", it lags behind the manufacturing sector. In some studies, it is stated that the Construction 4.0 concept, together with digital transformation in the construction sector, will achieve efficient results in the process from design to delivery (Sawhney et al., 2020). However, the use of Industry 4.0 technologies alone is not enough. Because while Industry 4.0 technologies form the technical infrastructure of the construction sector, they are lacking in the management approach. In this regard, new methods have been applied to improve the management approach. Lean thinking is one of these approaches. The application of LPDS, a project delivery system based on lean thinking, in the construction sector has been shown to yield much more efficient results compared to TPDS. Today, the integration of technology into the LPDS process as a new method has become a necessity. However, there are not enough studies in the literature focusing on the integration of LPDS with technology and examining its response in the sector. Therefore, the aim of this study is to highlight the importance of using Industry 4.0 technologies that will contribute to achieving the goals of lean thinking, which forms the basis of the developing LPDS in the construction sector. It is expected that the results of the study will contribute to research on the sector's development by raising awareness about the integration of LPDS and Industry 4.0 technologies.

Lean Construction and Lean Project Delivery System

Since the 1990s, the application of lean production principles and techniques in the construction sector has been investigated. The application of lean thinking, called "Lean Construction", to the construction sector was initiated by a research team in 1992 and is still ongoing today (Koskela, 1992; Koskela et al., 2002). For ensuring to facilitate the development, a community called the International Group for Lean Construction (IGLC) was formed and has been active since 1993.

The first study by Koskela (1992) is a prelude to the application of this paradigm to the construction sector. In his study, Koskela (1992) criticized construction project management on the grounds that traditional construction project management models construction as a series of transformation (value added) activities, while the new production philosophy increases competitiveness by identifying and eliminating wasteful (non-value added) activities. He argued that the construction sector should identify a new production system in line with the lean production paradigm and that this new paradigm should be researched, analyzed and adapted to the sector. Koskela (2000) synthesized three different perspectives (transformation, flow and value) in his study and formed the basis of lean construction. Koskela et al. (2002) introduced the concept of "Lean Construction" for the first time in their study and defined lean construction as "a method of designing production systems that aims to produce maximum value by minimizing material, time and labor wastage". LPDS appears as the project delivery system that enables the implementation of the lean process.

The term "project delivery system" is used to refer to the contractual structure of the project traditionally used, such as design-bid-build or design-build. In this context, the form of "delivery" is understood as a type of transaction and the key question is how to structure the transaction (Koskela & Howell, 2002). Design-build is seen as a way of providing a client with a single contracting organization with which to interact, as opposed to signing contracts with multiple players and thus taking on the task and risk of coordinating their actions. In contrast, the "Lean Construction Institute (LCI)" understands "delivery" in terms of the actual business processes used to move a facility from concept to client (Ballard & Zabelle, 2000) and identifies LPDS with the construction sector.

The LPDS, which enables the delivery of lean projects, shapes the project and delivery system for lean in the construction sector. The mission of the LCI is to develop a new and better way to design and build capital facilities. This new way is called LPDS (Ballard, 2000). Based on LCI's LPDS, the phases of the TPDS process (define, design, procure, assemble and deliver) are developed in accordance with the goals of lean thinking (faster and more efficient with less waste). In order to develop a lean construction framework, lean thinking needs to be emphasized at all stages of the construction process, from design to delivery of the facility. The next step after determining the way forward is to develop a transformational roadmap that integrates lean practices at each stage of the process (Aomar, 2012).

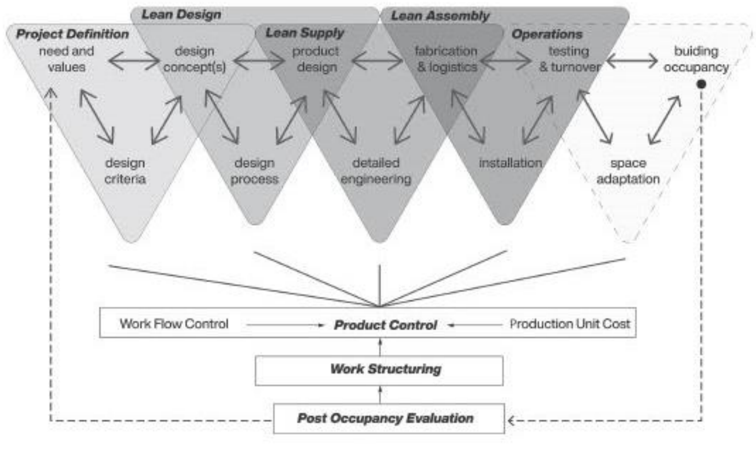

Figure 1: Lean project delivery system (Ballard, 2000 adapted by Pantazis et. al., 2022).

As seen in Figure 1, LPDS consists of 4 basic phases. These phases are defined as project definition, lean design, lean procurement and lean assembly. With the correct implementation of these phases, maximum efficiency can be achieved in the construction sector. Each phase includes three project steps. Each triangle represents an overlapping project phase, and some steps are part of two phases as project delivery is interlinked. Therefore, each project phase has an impact on the next phase and is influenced by the previous phase. Decisions made in one phase also affect other phases. Compared to TPDS, LPDS clearly shows the relationships and dependencies between different phases, which are often overlooked.

In LPDS, the task of the project team is not just to design and implement what the client wants, but to first help the client decide what they want and thus more accurately determine the needs of the project. This process constitutes the first phase of LPDS, the "defining the project" phase. One of the main objectives of this phase is to design how the product will be used (Ballard, 2008) before designing the product (facility).

Lean design is the most important step in achieving lean construction goals. This is because decisions to reduce waste at this stage will directly affect the procurement and construction phases. This phase continues with discussions between stakeholders to jointly develop process and product design based on conceptual design. In the lean design process, all actors of the project are involved in the process from the design process and all teams in the project process, from architects, engineers, contractors and subcontractors, work in coordination (Aydın, 2018).

The "lean procurement" phase consists of the procurement and delivery of design components and materials developed in lean design and the logistics management of inventories (Ballard, 2000). Lean procurement, one of the sub-processes of the lean construction approach, refers to the use of lean principles and JIT (Just-In-Time) principles in purchasing and transportation processes, and the creation of a supply chain in which the resources needed for production are supplied as much and when they are needed. Continuous control of inventory work saves time, storage space and excessive stock (Aydın, 2018) and this savings directly contributes to the reduction of cost items. One of the main objectives of this stage is to deliver the materials required at the construction site to the construction site frequently and in small quantities according to the work schedule (Tokat, 2015). For this purpose, products whose production and raw materials are close to each other are procured from a single supplier, the number of suppliers is kept to a minimum, and storage and stocking are reduced.

Lean assembly starts with the initial delivery of equipment and materials or components to the site and ends with the delivery of the work to the customer (Ballard, 2000). At this stage, the materials brought to the construction site with the understanding of the lean supply phase are used without waiting on the construction site and without any unnecessary consumption. Unnecessary use and consumption of all kinds of materials, labor and equipment that may arise during the manufacturing at the construction site are kept under control at this stage.

Lean construction is not limited to the design and construction phase. After installation, the "lean utilization" phase (Ballard, 2000; Ballard & Howell, 2003) begins with the commissioning and use of the facility. The utilization phase, which is an important component of the building life cycle, is also included in this process. The lean construction approach should also be maintained within the scope of maintenance, repair and renovation activities in the use phase until the building completes its lifetime.

Lean Construction and Industry 4.0

With changes and transformations from the past to the present, emerging technologies have contributed to all sectors, changing the structure of industries and the nature of competition (Porter & Heppelmann, 2014). The strategic position of the impact of emerging technologies on the transformation of organizations intersects with the underlying benefits of Industry 4.0 (Xu et al., 2018) in manufacturing, where a digital environment is made possible by triggering greater efficiency, competition and innovation.

Based on lean thinking, it aims to minimize waste through many organizational practices, rather than emphasizing the implementation of modern technologies or enterprise resource planning. On the other hand, various research studies show that implementing Industry 4.0 technologies is characterized by performance benefits ranging from increased flexibility to improved productivity, reduced cost, reduced lead time and improved quality (Dombrowski et al., 2017).

Although the implementation of Industry 4.0 technologies in different sectors has many performance benefits, it has been seen to be insufficient because it is not a form of management. Satoglu et al. (2018) argue that the implementation of Industry 4.0 technologies cannot only solve the problems caused by mismanagement or disorganization, stating that in order for these technologies to be successfully realized, they must be implemented with lean activities before automation. Their study also emphasizes the importance of an effective flow of information before and after the implementation of these technologies. Considering all these, it has been a matter of curiosity how the lean approach applied alone and Industry 4.0 technologies affect the operational performance of various industrial sectors if they are integrated with each other.

When Industry 4.0 and lean production are examined in detail, it is realized that they are parallel to each other. In the early 1990s, efforts to integrate automation technology into lean production led to lean automation. Today, Industry 4.0 technologies are creating new solutions for lean automation, integrating Industry 4.0 and lean manufacturing, and beyond that, improving lean manufacturing with the increasing integration of information communication technologies. This accelerates the transition of Industry 4.0 from scientific research to real life. In addition, lean manufacturing systems support the successful and continuous implementation of Industry 4.0 in the manufacturing environment, as they provide an organization that focuses on business processes (Dobrowoski et al., 2017).

The powerful combination of lean manufacturing techniques and Industry 4.0 technologies can be adapted to the construction sector and is defined as "Lean Construction 4.0". It is argued that the Lean Construction 4.0 approach provides guiding principles to optimize operations, aiming to increase the efficiency, quality and sustainability of development processes in the construction sector through the use of lean principles and tools and Industry 4.0 technologies. Adopting this approach will enable a significant transformation in the construction sector.

In this context, Hatoum and Nassereddine (2022) propose a model for the construction sector, which they define as the "Lean Construction 4.0 House" (Figure 2). Any house needs a strong substrate to support it, and the most important substrate of the "Lean Construction 4.0 House" is "people". The human aspect is embedded in every element of the conceptual framework. Therefore, the innovations that Lean Construction 4.0 will bring to construction processes must meet human needs and respect the people involved, and the change between "people-technology-process" is the basis for creating the desired harmony (Hamzeh et al., 2021).

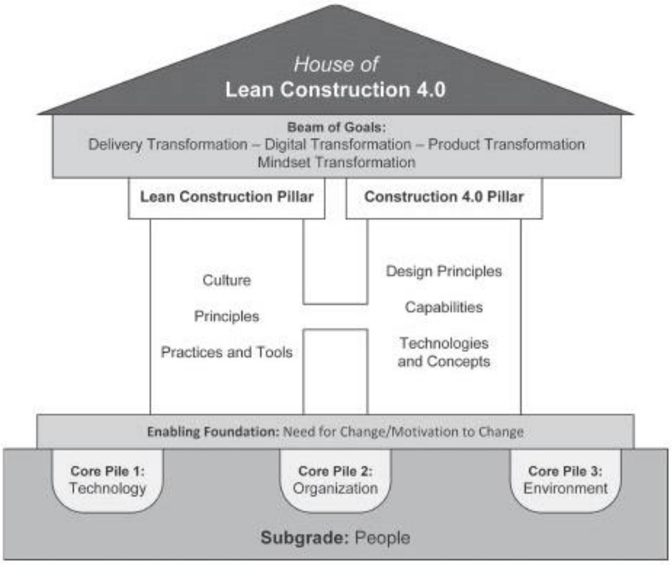

Figure 2: House of Lean Construction 4.0 (Hatoum & Nassereddine, 2022).

In order for people to implement the Lean Construction 4.0 vision, the necessary environment needs to be in place and companies need to be strategically positioned. It is therefore important to understand the factors that can influence an organization's decision towards Lean Construction 4.0. Three factors have been identified that influence change decisions in the construction sector; technology, organization and environment. Technology factors relate to the innovations offered by Lean Construction 4.0, organization factors include the organizational characteristics of firms in the construction sector and environmental factors are reflected in the external environment and innovations surrounding the organization (Hatoum & Nassereddine, 2022).

The Lean Construction 4.0 vision is inspired by the synergy of the two main pillars "Lean Construction" and "Construction 4.0" (Hamzeh et al., 2021). The concept of "Construction 4.0" opens up avenues and opportunities for integrating emerging technologies into project production and business processes in the construction sector (Sawhney et al., 2020). However, according to Cuvallar et al. (2020), this concept has not yet been presented with a robust, coherent and actionable framework for implementation that explicitly recognizes the interrelationships and autonomy of systems to make fully coordinated decisions. It is also argued that Construction 4.0 lacks a deep understanding of the links between emerging technologies and production management theory. "Lean Construction", on the other hand, provides production theory principles and a methodological framework for Construction 4.0. By adapting the "culture-philosophy-technology" triangle created by Lean 4.0 to the construction sector, which explicitly considers "principles and culture", "practices" and "tools and methods", Lean construction enables the formation of the people-process-technology triangle required for an "Industry 4.0" transformation in the sector.

The "goals beam" connecting the pillars of "Lean Construction" and "Construction 4.0" are the four main sector transformations enabled by the success of the "Lean Construction 4.0" vision. These transformations are product transformation, delivery transformation, digital transformation and mindset transformation.

Lean construction has the potential to enable Industry 4.0 in the construction sector and maximize intertwined synergies. Lean manufacturing principles have a natural extension to Industry 4.0. Satoglu et al. (2018) argue that a sense of purpose (production theory) and a problem-oriented view (lean-based methodologies) can be brought to bear on Industry 4.0 technologies. It is possible to relate this view to the construction sector. The Lean Construction 4.0 approach aims to increase the efficiency, quality and sustainability of development processes in the construction sector. It contributes to project and construction management objectives by strengthening data collection, analysis and decision-making capabilities in construction processes.

Conclusion

Today, as in many sectors, it is seen that traditional production methods are insufficient in the construction sector. Incomplete management activities in construction processes lead to wastage and as a result, an inefficient sector appears. In order to prevent this, new business models should be revealed for companies in the construction sector to make construction sites more efficient production areas by focusing on their efforts to increase productivity. As a result, in this study, it is tried to draw attention to the contributions of Industry 4.0, which will provide technical support to lean construction, which constitutes the adaptation of the lean concept that will affect the construction process at the operational level. The findings indicate significant potential for the construction sector through the integration of emerging Industry 4.0 technologies with lean construction practices. However, further efforts are needed to fully realize this integration. By leveraging their capabilities, construction companies can optimize the procurement of resources, improve project planning and execution, enhance collaboration and ultimately deliver higher quality projects in shorter timeframes and at lower costs. By effectively utilizing Industry 4.0 technologies, it will be possible to more successfully achieve the time, cost and quality targets of lean construction projects.

In the current timeframe, the change of all old thinking models and the commitment of all stakeholders to comply with a single master plan reveals the necessity of an effective management model. While the results of the study are expected to form a basis for the field of application and science, it is recommended that studies be carried out to determine the technologies that can be integrated into the LPDS that constitute the lean construction process in the future.

References

Al-Aomar, R. (2012). A lean construction framework with Six Sigma rating. *International Journal of Lean Six Sigma, 3*(4), 299-314.

Aydın, H. (2018). *Yalın yönetim anlayışının çalışanların motivasyonuna ve hizmet kalitesine etkilerine yönelik bir araştırma* [Unpublished doctoral dissertation]. Istanbul Gelisim University.

Aydın, N. (2015). Yalın düşünce sisteminin üretime sağladığı katkılar. *Anadolu Bil Meslek Yüksekokulu Dergisi*, (37), 23-37.

Ballard, G., & Howell, G. (2003). Lean project management. *Building Research & Information*, *31*(2), 119-133.

Ballard, G. (2000). Lean project delivery system. *LCI White Paper No. 8*, September 23, revision 1.

Ballard, G. (2008). The lean project delivery system: An update. *Lean construction journal*, *2008*, 1-19.

Dombrowski, U., Richter, T., & Krenkel, P. (2017). Interdependencies of Industrie 4.0 & lean production systems: A use cases analysis. *Procedia Manufacturing*, *11*, 1061-1068.

Duman, E. (2011). *Krizlerin anatomisi: 1929 ekonomik buhranı ile 2008 küresel krizinin karşılaştırılması* [Unpublished master's thesis]. Karamanoglu Mehmetbey University.

Hamzeh, F., González, V. A., Alarcon, L. F., & Khalife, S. (2021). Lean construction 4.0: Exploring the challenges of development in the AEC industry. In *Proceedings of the 29th Annual Conference of the International Group for Lean Construction (IGLC), Lima, Peru* (pp. 207-216).

Hatoum, M. B., Nassereddine, H., & Badurdeen, F. (2021). Reengineering construction processes in the era of construction 4.0: A lean-based framework. In *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC)* (pp. 403-412).

Hatoum, M. B., & Nassereddine, H. (2022). Proposing a house of lean construction 4.0. In V. A. González, F. Hamzeh, & L. F. Alarcón, (Eds.), *Lean Construction 4.0: Driving a Digital Revolution of Production Management in the AEC Industry* (pp. 50-67). Routledge.

Karal, F. S. (2019). *Dijital dönüşümün proje yöneticilerinin yetkinlikleri üzerindeki etkisinin incelenmesi* [Unpublished master's thesis]. Istanbul Technical University.

Koskela, L. (1992). *Application of the new production philosophy to construction* (Technical Report Vol. 72, p. 39). Center for Integrated Facility Engineering (CIFE), Stanford University.

Koskela, L., Howell, G., Ballard, G., & Tommelein, I. (2002). The foundations of lean construction. In *Design and construction* (pp. 211-226). Routledge.

Kömürcü, A. M. (2007). İnşaat sektöründe yalın proje yönetimi [Unpublished doctoral dissertation]. Erciyes University.

Pantazis, E., Koc, E., & Soibelman, L. (2022). The Implications of the 4.0 revolution in the AEC industry on the lean construction paradigm: Identifying the status quo and drawing the path forward. In V. A. González, F. Hamzeh, & L. F. Alarcón, (Eds.), *Lean Construction 4.0: Driving a Digital Revolution of Production Management in the AEC Industry* (pp. 35-49). Routledge.

Porter, M. E., & Heppelmann, J. E. (2014). How smart, connected products are transforming competition. *Harvard business review*, *92*(11), 64-88.

Satoglu, S., Ustundag, A., Cevikcan, E., & Durmusoglu, M. B. (2018). Lean production systems for industry 4.0. *Industry 4.0: Managing the digital transformation*, 43-59.

Sawhney, A., Riley, M., & Irizarry, J. (2020). Construction 4.0: Introduction and overview. In *Construction 4.0* (pp. 3-22). Routledge.

Tokat, A. (2015). *Türk yapım şantiyelerindeki israfların ve nedenlerinin tespit edilmesi ve yalın inşaat uygulamalarıyla çözüm önerisi geliştirilmesi* [Unpublished master's thesis]. Istanbul Technical University.

Toker, E. (2022). *Yalın düşünce yöntemine dayalı kauçuk hortum imalatında değer akışı haritalandırma analizi* [Unpublished master's thesis]. Maltepe University.

Xu, G., Li, M., Chen, C. H., & Wei, Y. (2018). Cloud asset-enabled integrated IoT platform for lean prefabricated construction. *Automation in Construction*, *93*, 123-134.

Machine Learning-Driven Structural Analysis of Lifting Self-Forming GFRP Elastic Gridshells

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Abstract

The assessment of structural performance is critical for ensuring the safety and longevity of structures built. This study investigates a crucial element of structural damage assessment; the prediction of structural performance for glass fiber reinforced polymer (GFRP) elastic gridshell structures. Utilizing machine learning (ML) methodologies, various algorithms such as linear regression (LR), ridge regression (RR), support vector regression (SVR), K-nearest neighbors (KNN), decision tree (DT), random forest (RF), adaptive boosting (AdaBoost), extreme gradient boosting (XGBoost), category boosting (CatBoost), and light gradient boosting machine (LightGBM) are deployed to forecast the maximum stress. Moreover, first-order and second-order sensitivity analyses are performed to demonstrate the importance of input variables on the output. Through a comparative analysis, CatBoost emerges as the most accurate model, showcasing its potential for enhancing predictive accuracy in structural performance evaluation.

Keywords: *gridshell structure, machine learning, regression, structural analysis, sensitivity analysis.*

Introduction

Lately, there has been a notable increase in the desire for environmentally friendly buildings. A pivotal strategy in achieving eco-conscious construction involves meticulous selection of materials and systems, guided by life cycle assessments and environmental impact evaluations. Among the plethora of options available, the gridshell structure is considered a beacon of sustainability and efficiency, owing to its lightweight composition and expansive coverage capabilities. Numerous investigations have been carried out to examine the gridshell framework, focusing on its design rooted in the deformation of a flat grid lacking in-plane shear rigidity, and its notable double-curvature shape (Kookalani et al., 2021, 2022; Kookalani & Aung, 2023; Kookalani & Cheng, 2021, 2022; Tayeb et al., 2013).

In the existing literature, interest in further analyses of this structure remains, in relation to their resilience, longevity and environmental friendliness. Among prevailing studies, finite element analysis (FEA) is commonly utilized for structural analysis due to its accuracy. This method is intricate and time intensive. Consequently, there is a growing demand for alternative methods that offer swift and straightforward computational solutions. Recent years have seen the emergence of data-driven techniques as viable substitutes for lengthy simulation processes.

These approaches tackle structural engineering challenges with minimal computational burden while maintaining high accuracy levels (Fan et al., 2021; Xu et al., 2021). This move towards methodologies guided by data marks a promising path for improving the effectiveness and availability of structural analysis across different engineering fields.

Data-driven methods, primarily powered by machine learning (ML) within the realm of artificial intelligence (AI), have emerged as pivotal tools in structural engineering. Mangalathu et al. (2020) utilized ML models such as LightGBM, CatBoost, AdaBoost, and XGBoost to identify seismic failure modes. Guo et al. (2021) undertook a comparison of multiple ML models, encompassing multilayer perceptron neural networks, support vector machine (SVM), K-nearest neighbors method, logistic regression, classical naive Bayesian classifier, ensemble techniques, and various tree-based classifiers, for soil liquefaction prediction. Huang and Burton (2019) utilized ML techniques to detect in-plane failure modes of RC frames with infills, highlighting the reasonable accuracy of SVM and adaptive boosting algorithms. These studies collectively underscore the transformative potential of data-driven ML techniques in revolutionizing structural engineering practices.

This paper conducts a comprehensive comparative analysis of various ML models, including LR, RR, SVR, KNN, DT, RF, AdaBoost, XGBoost, CatBoost, and LightGBM, to forecast the structural performance of gridshells. The aim is to identify the model yielding the highest accuracy. A dataset of 400 samples is created by FEM for this investigation. To optimize the performance of each ML model, a combination of grid search technique and K-fold cross-validation (CV) is employed to fine-tune parameters. Furthermore, first-order and total-effect sensitivity analyses (SA) are conducted across different ML approaches.

Sensitivity Analysis

Saltelli et al. (2008) introduced a variance-based SA technique for assessing the influence of alterations in model input variables on corresponding output values. This method explores how input features and output factors interact. It keeps input parameter values constant while methodically adjusting a single input parameter (Liu et al., 2020; Vu-Bac et al., 2019).

First-order Sensitivity Indices

In the multivariate k-input model, the measurement vector can be represented as $y=f(x_1, x_2, \ldots, x_k)$. The computation of the first-order index is conducted as follows:

$$S_i = \frac{V_{x_i}[E_{x\sim i}(y|x_i)]}{V(y)} \quad (1)$$

where $V_{x_i}[E_{x\sim i}(y|x_i)]$ computes the influence of the variable x_i on the outcome, while keeping x_i constant; $E_{x\sim i}(y|x_i)$ represents the fluctuation in the average value $E(y)$; $V(y)$ denotes the overall variance of y regardless of any conditions.

Total-effect Sensitivity Indices

To capture the entirety of output variance, it is necessary to expand beyond first-order indices of coupling terms. While first-order indices assess a portion of output variation linked to the variance of input variable x_i, higher-order indices are required for a comprehensive evaluation. Therefore, the overall impact S_T is utilized to measure how the input variable x_i affects the variance of the output. The calculation of the total effect index is outlined below:

$$S_T = 1 - \frac{V_{x_{\sim i}}[E_{xi}(y|x_{\sim i})]}{V(y)} \tag{2}$$

where $E_{x_i}(y|x_{\sim i})$ denotes the mean value of y when all variables except x_i are fixed, while $V_{x_{\sim i}}\left[E_{x_i}(y|x_{\sim i})\right]$ represents its variation. It is crucial to emphasize that the difference between Si and S_T demonstrates how the input variables interact with x_i.

Numerical Example

The quality and quantity of samples play a pivotal role in shaping the performance of ML methodologies. Thus, the meticulous preparation of a suitable dataset stands as a fundamental task within this domain. One approach to achieving this is through the implementation of generative design methods, offering a practical means to generate a diverse array of forms by manipulating key features and analysing resultant outcomes. Initially, feature values are designated to facilitate the creation of shell structures. Subsequently, a grid is superimposed onto the continuous shell via the compass approach, enabling the generation of a regular quadrilateral grid across various shell configurations. This method yields an assortment of shapes by iteratively adjusting design variables such as heights, curvatures, and border forms. In this study, eight input variables, comprising height (H_1, H_2, H_3), width (D_1, D_2, D_3), length (S), and grid size (G), are explored, as depicted in
Figure 1a. Table 1 delineates the parameter ranges explored, with a total of 400 samples being generated using the aforementioned methodology within the specified parameter bounds.

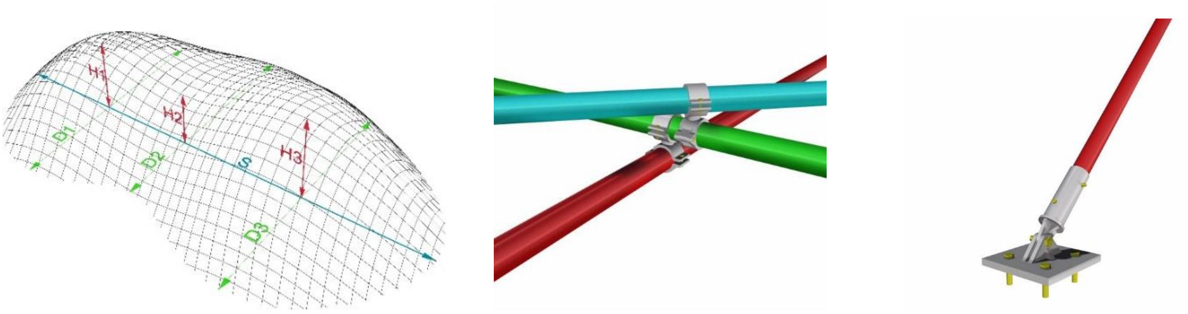
Table 1. Statistical attributes of dataset.

Attribute	Unit	Minimum	Maximum	Average
H_1	m	4	8	6
H_2	m	4	8	6
H_3	m	4	8	6
D_1	m	14	18	16
D_2	m	13	22	17.5
D_3	m	16	20	18
S	m	32	37	34.5
G	m	0.5	3	1.75
$f(x)$	MPa	3.22	27.82	15.52

The structural performance analysis of the generated samples involves FEA, which incorporates parameters such as maximum stress. Gridshell structures are modelled using FEA, with beam component B32 serving to simulate members and accurately calculate axial forces, shear, and bending moments (Xiang et al., 2020a). These gridshell components consist of circular tubes made of glass fiber reinforced polymer (GFRP), with a density of 1850 kg/m³ and a Young's modulus of 26 GPa. These tubes have a wall thickness of 4 mm and an outer radius of 25 mm. Moreover, the relationships among structural components, demonstrated through swivel scaffold connections, are emulated to limit movements perpendicular to the plane and movements parallel to the plane, as depicted in

Figure 1b. Pinned supports are strategically placed at the ends of beams to secure the gridshells firmly to the ground, as illustrated in

Figure 1c (Xiang et al., 2021). In FEA, the equipment load is estimated at 2 kN/m^2, while the structural self-weight is determined using a gravitational acceleration of 9.8 N/kg. Beam element lengths are constrained to 200 mm for analysis efficiency (Xiang et al., 2020b). The key structural performance factor, stress prediction $f(x)$, is identified for ML model evaluation. The dataset is split into training and testing portions, with 70% allocated for training and 30% for testing. This division allows for training ML algorithms and evaluating their efficiency afterward. This process culminates in the establishment of a comprehensive table featuring design factors and corresponding outputs.



(a) (b) (c)

Figure 1: Gridshell simulation: (a) Design variables of gridshells; (b) Swivel scaffold connection; (c) Pin anchorage for beam ends.

Figure 2 depicts a correlation matrix that displays the connections between input parameters. Each coefficient in the matrix measures the level of interaction between two parameters. The analysis reveals a significant association between variable D_3 and D_1, with a correlation coefficient of 0.87, indicating a strong relationship. Additionally, the correlation coefficient between D_1 and D_2 stands at 0.48, suggesting a moderate correlation. However, no discernible correlations emerge for the remaining parameters. In pursuit of identifying the most effective ML technique, an array of models including LR, RR, SVR, KNN, DT, RF, alongside gradient boosting methods such as AdaBoost, XGBoost, CatBoost, and LightGBM, have been thoroughly investigated.

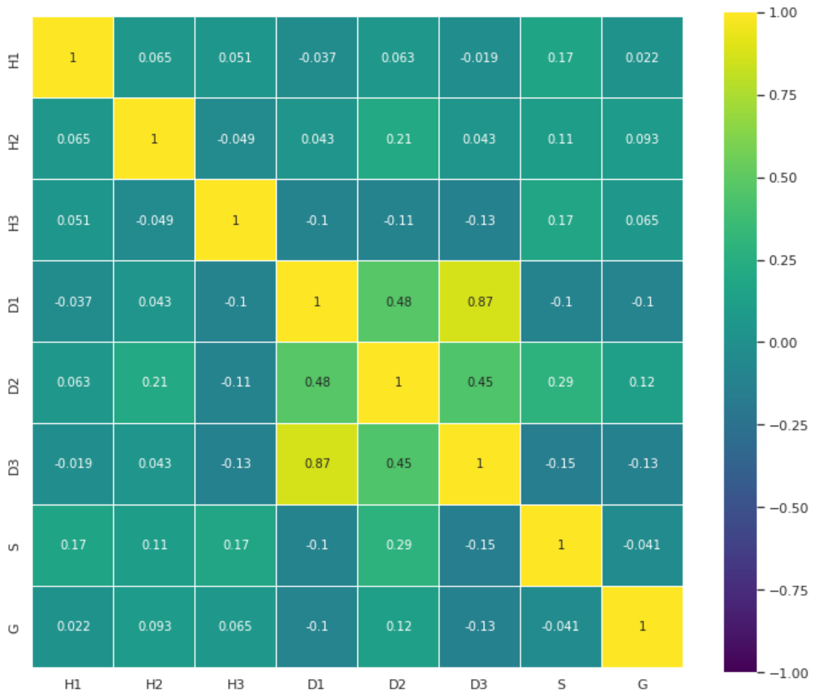


Figure 2: Correlation matrix for input variables.

Stress Prediction

This study aims to examine a key aspect of structural analysis in terms of its performance. Given that damage typically occurs in members experiencing excessive stress, it is crucial to manage stress levels within the elements. Therefore, the foremost outcome to ponder is the maximum stress. The stress present in the gridshell components can be expressed as:

$$\sigma_x = \frac{F_x}{A} \pm \frac{M_y}{W_y} \pm \frac{M_z}{W_z} \tag{3}$$

$$\tau_y = \frac{F_y}{A} \tag{4}$$

$$\tau_z = \frac{F_z}{A} \tag{5}$$

where the symbols σ and τ represent nominal and shear stress, respectively. A stands for the cross-sectional area of the member, while F represents forces. W signifies the bending modulus of sections, and M refers to the inner moments of sections. Thus, the initial result can be described as:

$$f_{\square}(x) = \sigma_{v\max} = \left(\sqrt{\sigma_x^2 + 3\tau_y^2 + 3\tau_x^2}\right)_{\max} \tag{6}$$

where $\sigma_{v\max}$ represents the highest level of stress.

Hyper Parameters Fine-tuning

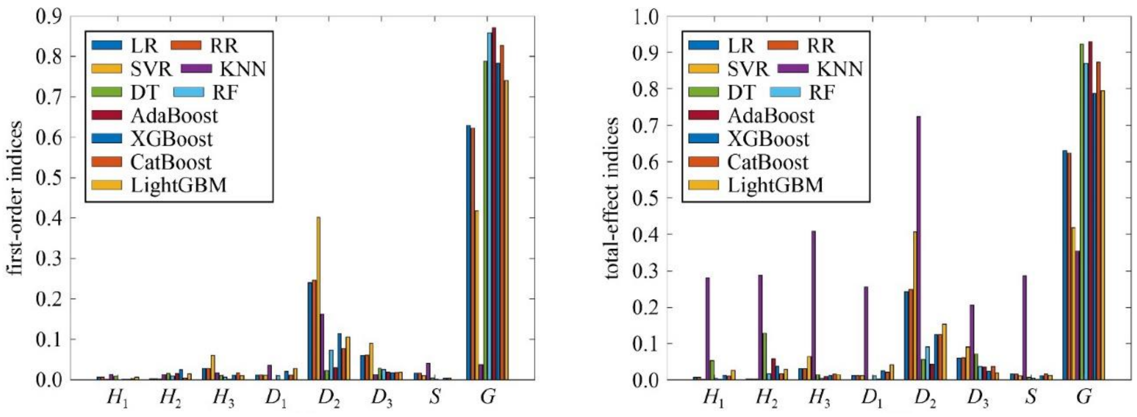
The optimization of ML model hyperparameters involves employing a grid search method and conducting 10-fold CV to prevent overfitting. This process selects the hyperparameter values that yield the best performance for the ML techniques. Table 2 illustrates the optimal hyperparameter values for each ML algorithm.

Table 2. Optimal hyper parameters for *f*(*x*).

Model	Optimal configuration
LR	N/A
RR	alpha=1
SVM	Kernel=RBF, C=30, degree=1, epsilon=0. 1
KNN	Leaf_size=10, n_neighbors=1, p=3
DT	Max_depth=8, min_samples_leaf=1, min_samples_split=2, random_state=2
RF	Max_depth=8, max_features=3, n_estimators=500
AdaBoost	Learning_rate=0.1, n_estimators=200, random_state=0
XGBoost	Colsample_bytree=0.4, learning_rate=0.08, max_depth=2, n_estimators=1000
CatBoost	Depth=6, iterations=2000, learning_rate=0.1
LightGBM	Colsample_bytree=0.9, learning_rate=0.1, max_depth=4, n_estimators=500

Sensitivity Analysis

The first-order (S_i) and total effect (S_T) sensitivity indices derived from the regression models depicted in Figure 3 ascertain the influence of input variables. The indices indicate independence among the input variables, as they closely match across all ML methods, with exceptions in KNN and DT models. Among these variables, G emerges as the most influential, while H_1 appears to have minimal impact on $f(x)$. Neglecting the influence of G could lead to decreased accuracy in output predictions. Following G, D_2 ranks as the second most influential variable. Conversely, H_1 and S exhibit minimal influence on $f(x)$, rendering them insignificant. Consequently, in future studies, prioritizing the consideration of significant variations in G and D_2 within the dataset can enhance accuracy while reducing the required sample size.



(a) (b)

Figure 3: SA of *f*(*x*): (a) First-order; (b) Total-effect.

Regression Models for Stress Prediction

Figure 4 showcases regression plots comparing various ML models, conclusively highlighting the superior accuracy of the CatBoost model. This assertion is further supported by the findings presented in Table 3, depicting the average coefficient of determination (R^2) and root mean square error (*RMSE*) values derived from 10-fold CV. The CatBoost model yields the lowest *RMSE* at 1.124 and the highest R^2 at 0.930. the lowest accuracy is for RR method, with lowest R^2 at 0.120.

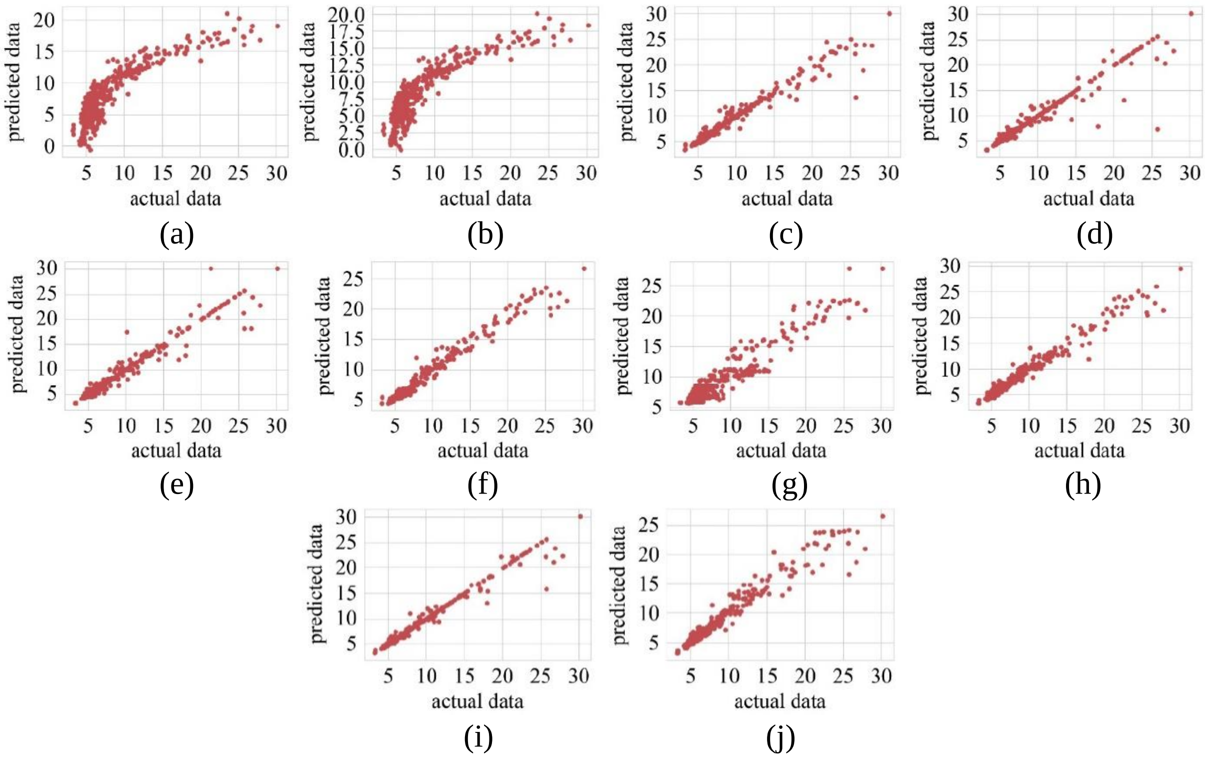


Figure 4: Regression plot of $f(x)$: (a) LR; (b) RR; (c) SVR; (d) KNN; (e) DT; (f) RF; (g) AdaBoost; (h) XGBoost; (i) CatBoost; (j) LightGBM.

Table 3. Performance of ML based regression models for $f(x)$ prediction of gridshells.

Regression method	Average R^2	Average *RMSE*
LR	0.124	2.515
RR	0.120	2.514
SVR	0.371	2.727
KNN	0.822	1.682
DT	0.779	1.750
RF	0.871	1.342
AdaBoost	0.593	1.824
XGBoost	0.905	1.126
CatBoost	**0.930**	**1.124**
LightGBM	0.890	1.278

Conclusions

In conclusion, this study delves into the development of ML methodologies for predicting the structural performance of GFRP elastic gridshells under self-weight conditions. Several ML algorithms, including LR, RR, SVR, KNN, DT, RF, AdaBoost, XGBoost, CatBoost, and

LightGBM, are scrutinized to identify their efficacy in this task. The examination is based on FEA, and tests conducted on 400 gridshell structures to compile a robust dataset for training and testing the ML models.

Each ML model is fed with eight key features derived from gridshell dimensions and grid size, while the output comprises maximum stress levels. Through a meticulous process involving grid search and K-fold CV, optimal hyperparameters are identified for each ML algorithm. From the test, SA provides deeper insights into how input variables affect the output, yielding first-order (S_i) and total-effect (S_T) sensitivity indices. Generally, there are minimal discrepancies between S_i and S_T across most ML models, suggesting limited interaction among input variables.

Upon comparative analysis, the CatBoost model emerges as the most accurate, with distinguishing R^2 values of 0.930, along with the lowest RMSE values. Conversely, LR and RR models demonstrate comparatively lower accuracy. This study not only contributes to advancing ML techniques in predicting the performance of GFRP elastic gridshells under self-weight but also underscores the potential of CatBoost as a powerful tool in structural engineering, thereby facilitating more informed decision-making in design and construction processes.

Acknowledgments

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References

Fan, W., Chen, Y., Li, J., Sun, Y., Feng, J., Hassanin, H., & Sareh, P. (2021). Machine learning applied to the design and inspection of reinforced concrete bridges: Resilient methods and emerging applications. *Structures*, *33*, 3954–3963. https://doi.org/10.1016/j.istruc.2021.06.110

Guo, H., Zhuang, X., Chen, J., & Zhu, H. (2021). Predicting earthquake-induced soil liquefaction based on machine learning classifiers: A comparative multi-dataset study. *International Journal of Computational Methods*, 2142004. https://doi.org/10.1142/S0219876221420044

Huang, H., & Burton, H. V. (2019). Classification of in-plane failure modes for reinforced concrete frames with infills using machine learning. *Journal of Building Engineering*, *25*, 100767. https://doi.org/10.1016/j.jobe.2019.100767

Kookalani, S., & Aung, H. H. (2023). GFRP elastic gridshell structures: A review of methods, research, applications, opportunities, and challenges. *Journal of Civil Engineering and Materials Application*, *7*(2), 71–94. https://doi.org/10.22034/JCEMA.2023.401834.1111

Kookalani, S., & Cheng, B. (2021). Structural analysis of GFRP elastic gridshell structures by particle swarm optimization and least square support vector machine algorithms. *Journal of Civil Engineering and Materials Application*, *5*(3), 139–150. https://doi.org/10.22034/JCEMA.2021.304981.1064

Kookalani, S., & Cheng, B. (2022). Structural performance prediction of GFRP elastic gridshell structures by artificial neural network. *6th International Conference on Applied Researches in Science and Engineering*.

Kookalani, S., Cheng, B., & Xiang, S. (2021). Shape optimization of GFRP elastic gridshells by the weighted Lagrange ε-twin support vector machine and multi-objective particle swarm optimization algorithm considering structural weight. *Structures*, *33*, 2066–2084. https://doi.org/10.1016/j.istruc.2021.05.077

Kookalani, S., Nyunn, S., & Xiang, S. (2022). Form-finding of lifting self-forming GFRP elastic gridshells based on machine learning interpretability methods. *Structural Engineering and Mechanics*, *84*(5), 605–618.

Liu, B., Vu-Bac, N., Zhuang, X., & Rabczuk, T. (2020). Stochastic multiscale modeling of heat conductivity of Polymeric clay nanocomposites. *Mechanics of Materials*. https://doi.org/10.1016/j.mechmat.2019.103280

Mangalathu, S., Jang, H., Hwang, S. H., & Jeon, J. S. (2020). Data-driven machine-learning-based seismic failure mode identification of reinforced concrete shear walls. *Engineering Structures*, *208*, 110331. https://doi.org/10.1016/j.engstruct.2020.110331

Saltelli, A., Ratto, M., Andres, T., Campolongo, F., Cariboni, J., Gatelli, D., Saisana, M., & Tarantola, S. (2008). Global sensitivity analysis: The primer. In *Global Sensitivity Analysis: The Primer*. https://doi.org/10.1002/9780470725184

Tayeb, F., Caron, J. F., Baverel, O., & Du Peloux, L. (2013). Stability and robustness of a 300 m2 composite gridshell structure. *Construction and Building Materials*, *49*, 926–938. https://doi.org/10.1016/j.conbuildmat.2013.04.036

Vu-Bac, N., Zhuang, X., & Rabczuk, T. (2019). Uncertainty quantification for mechanical properties of polyethylene based on fully atomistic model. *Materials*. https://doi.org/10.3390/ma12213613

Xiang, S., Cheng, B., & Kookalani, S. (2020b). An analytic solution for form finding of GFRP elastic gridshells during lifting construction. *Composite Structures*, *244*. https://doi.org/10.1016/j.compstruct.2020.112290

Xiang, S., Cheng, B., Kookalani, S., & Zhao, J. (2021). An analytic approach to predict the shape and internal forces of barrel vault elastic gridshells during lifting construction. *Structures*, *29*, 628–637. https://doi.org/10.1016/j.istruc.2020.11.032

Xiang, S., Cheng, B., Zou, L., & Kookalani, S. (2020a). An integrated approach of form finding and construction simulation for glass fiber-reinforced polymer elastic gridshells. *Structural Design of Tall and Special Buildings*, *29*(5), e1698. https://doi.org/10.1002/tal.1698

Xu, Y., Zhang, M., & Zheng, B. (2021). Design of cold-formed stainless steel circular hollow section columns using machine learning methods. *Structures*, *33*, 2755–2770. https://doi.org/10.1016/j.istruc.2021.06.030

Blockchain Integrated Supply Chain Management in Construction Industry: Literature Review

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Abstract

As we embrace Industry 4.0, the call for digitalization intensifies. Blockchain (BC) technology, a driving force in this transformation, is gaining prominence within the construction industry (Construction 4.0). BC's decentralized, transparent, and immutable data and transaction records make it a valuable tool for managing construction processes, including supply chain management (SCM). Despite its potential, research on BC-integrated SCM in construction remains fragmented. This study aims to organize and present existing research through a systematic bibliometric review using Scopus and VOSviewer. By categorizing findings into thematic clusters, we provide a holistic understanding of BC's application in construction SCM. Our integrative perspective contributes unique value to the field.

Keywords: *blockchain (BC), building information modelling (BIM), construction industry, distributed ledger technology (DLT), industry 4.0, internet of things (IoT), supply chain management (SCM), smart contract (SC), traceability.*

Introduction

In Industry 4.0, the construction industry undergoes transformative shifts, particularly in SCM. BC technology offers enhanced transparency, efficiency, and collaboration. Our literature review synthesizes current research, identifies gaps, and suggests future directions.

Traditionally, construction lags in digital adoption during the Fourth Industrial Revolution. BC can revolutionize SCM by providing an immutable record system, fostering trust and efficiency (Hewavitharana et al., 2019). Research highlights BC's potential to address productivity and collaboration challenges, necessitating further exploration, including integration into project management (Liu et al., 2023).

Growing interest in BC in construction calls for practical research to validate theoretical concepts. Future studies should assess BC's real-world benefits, compatibility with various project management systems, and broader industry applications. Analyzing BC's cost-effectiveness (Liu et al., 2023) and integrating it into construction management (Pech & Vrchota, 2022) are crucial. Wu et al. (2022) advocate for technology integration in construction management.

The Impact of BC Technology on Construction SCM

BC technology is transforming SCM in construction, offering clarity, efficiency, and accountability. Smart contracts streamline procurement, ensuring transparent transactions and minimizing delays (Tezel et al., 2020). Integrating BC with project delivery systems enhances efficiency and transparency (Liu et al., 2023). Its immutable nature provides a robust audit trail, curbing fraud and promoting accountability (Wang et al., 2021). BC works with IoT and BIM for real-time material tracking and project monitoring (Petersen et al., 2021). Additionally, BC promotes sustainability by documenting material origins and life cycles, aiding eco-friendly decisions (Kshetri, 2021). As BC evolves, its applications in construction SCM will expand, leading to more streamlined, secure, and sustainable practices. Future research should focus on cost-effectiveness, integration with project delivery systems, and technology convergence in construction management (Liu et al., 2023). In summary, BC's integration into construction SCM enhances security, efficiency, and environmental stewardship.

Research Methodology

In this paper, we use a systematic-bibliometric literature review to capture the essence of BC research in the construction industry. This method helps craft research questions, identify research gaps, lay the groundwork for new frameworks, and test theoretical hypotheses. We utilize the Scopus database for its reliability and extensive coverage (Karasözen et al., 2021). Our study reviews BC's role in construction SCM, drawing from Scopus-indexed literature from 2016 to 2024. Figure 1 shows our step-by-step research method.

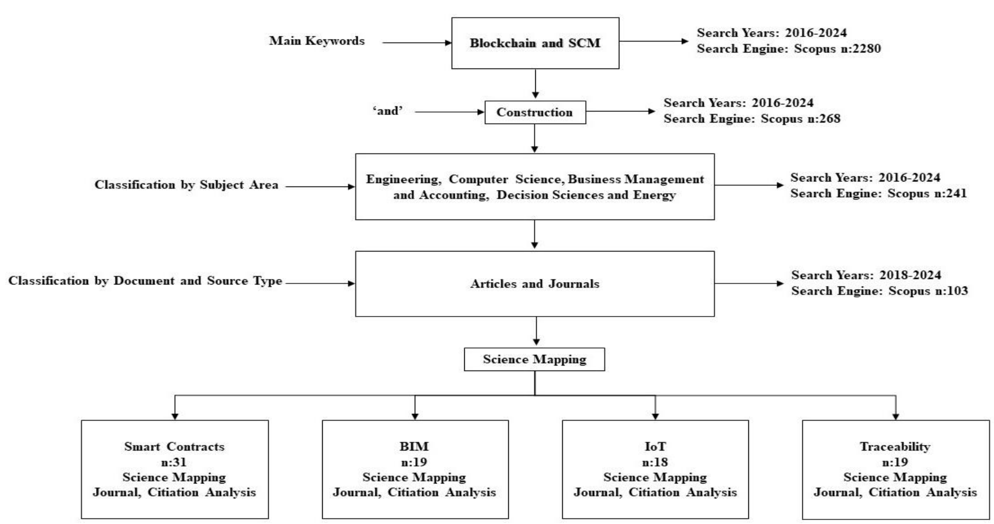


Figure 1: The research method diagram.

We compiled a dataset of 2,280 studies using the search terms "BC" and "SCM." These studies were analyzed based on sectoral focus, geographical distribution, and research themes. Initially, 268 studies were gathered, and after refinement, including selecting reputable academic journal articles, 103 relevant studies emerged. The predominant research fields were Engineering (31.6%), Computer Science (21.2%), and Business Management and Accounting (14.2%). China led with 43 studies, followed by the United Kingdom (17), Australia (11), the United States (10), and both India and Malaysia (8 each).

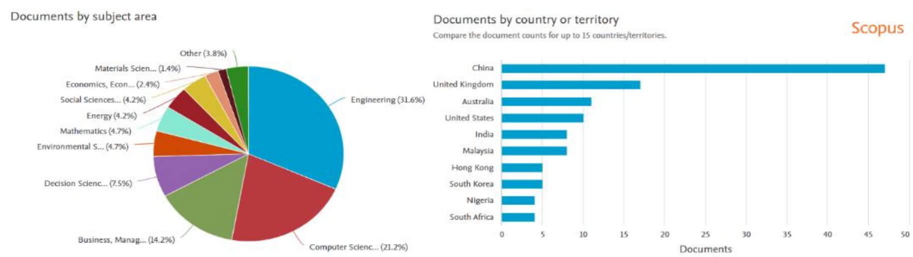
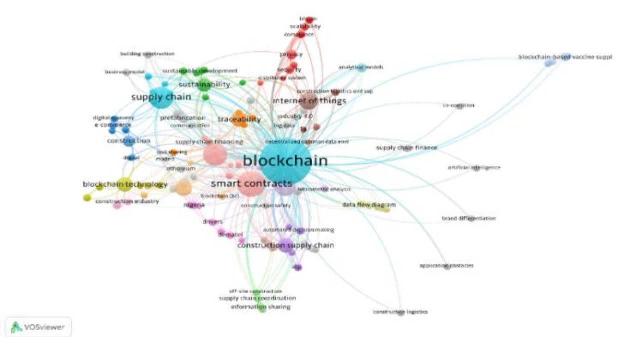


Figure 2: Relevant studies Scopus research areas and country diagrams.

In this research, we categorized key studies into four main themes: SC, BIM, IoT, and traceability. SC and BIM were the most frequently explored topics in conjunction with BC and SCM. Science mappings, including BC, SCM, and construction-related keywords, were created and shown in Figures 3 and 4. Using VOSviewer, we visualized the interconnections between BC technologies and these themes, then narrowed our focus to the construction sector and refined sub-keywords. VOSviewer's mapping illustrated these clusters. We conducted a bibliometric analysis, examining citation frequency and journal distribution for each theme, and analyzed and contrasted the content and types of papers. Finally, we critically discussed the findings, identified gaps, and addressed the study's limitations and practical implications.



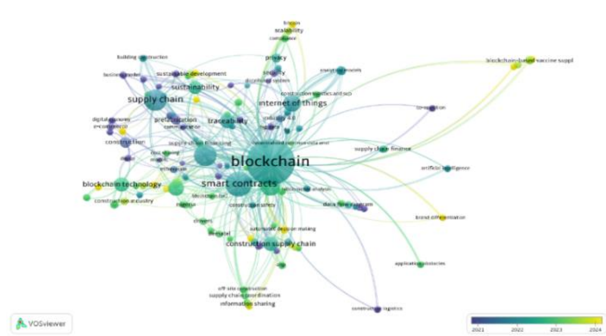


Figure 3 - 4: The science mapping of BC, SCM and construction related keywords and occurrence by VOSviewer & The timeline science mapping of BC, SCM and construction related keywords by VOSviewer.

Findings

BC Integrated SCM in Construction & SC: Recently, the construction industry has seen growing interest in DLT and SC applications. This section explores key studies highlighting their transformative potential. We analyzed 31 relevant studies, with the most cited contexts shown in Table 1 according to hierarchical citation.

Table 1. Most cited studies of BC, SCM, construction and SC related keywords.

Sources	Context of Studies
Wang et al. (2020)	Researchers introduced a BC structure to boost supply chain oversight and information sharing in precast construction, with SC ensuring standard compliance.
Wan et al. (2020)	Researchers examined how BC facilitates supply chain information sharing, emphasizing SC for enhancing collaborative decision-making.
Wang et al. (2021)	Researchers crafted a supply chain design using BC, where SC play a key role in ensuring transaction integrity and efficiency.
Lu et al. (2021)	Researchers investigated smart construction objects as BC oracles, with SC automating SCM in construction.
Hamledari & Fischer (2021)	Researchers explored the integration of crypto assets into construction supply chains, with SC bridging physical and financial aspects.
Nanayakkara et al. (2021)	Researchers proposed using BC and SC to resolve payment disputes in construction supply chains.
Kiu et al. (2022)	Researchers reviewed BC in construction, highlighting SC as a trust-building mechanism that ensures transparency.
Elghaish et al. (2023)	Researchers introduced a BIM-BC integrated model for construction supply chains, where SC enforce circular economy principles.
Brandín & Abrishami (2021)	Researchers focused on BC for asset data lifecycle, with SC ensuring data traceability and security.
Hamledari & Fischer (2021)	Researchers assessed how BC and SC enhance the visibility of construction supply chains.
Xu et al. (2021)	Researchers developed a BC-based management scheme for manufacturing supply chains, where SC facilitate intelligent operations.

In summary, these studies highlight the potential of BC and SC in transforming the construction industry. As the industry evolves, further research and practical applications will drive innovation and efficiency.

According to Figure 6, BIM is the most trending tool in SC. Other key topics include payment, asset life cycle, built environment, lean construction, sustainability, network analysis, and project management in Industry 4.0. Figure 7 shows the analysis of citations and journals on these issues: Automation in Construction has 496 citations, IEEE Access has 101, and the International Journal of Production Research has 89.

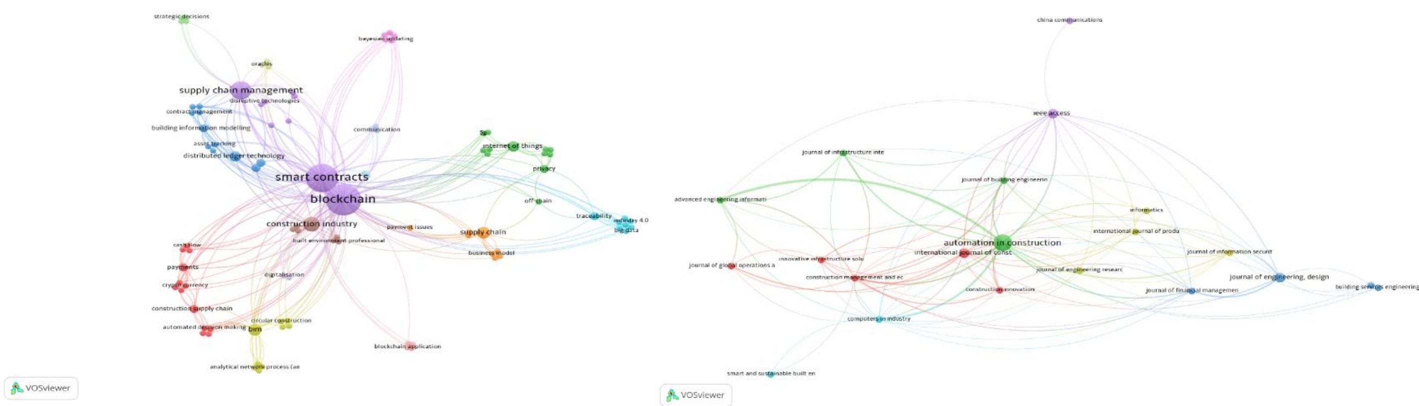


Figure 6 - 7: The science mapping of BC, SCM, construction and SC related keywords & occurrence and the analyses of journal and citations BC, SCM, construction and SC related keywords & occurrence by VOSviewer.

BC Integrated SCM in Construction & BIM: In the evolving construction sector, BIM stands out as a pivotal technological advancement. This section explores key research showcasing its revolutionary impact. We analyzed 19 relevant studies, with the most cited contexts shown in Table 2 based on hierarchical citation.

Table 2. Most cited studies of BC, SCM, construction and BIM related keywords.

Sources	Context of Studies
Li et al. (2021)	Researchers developed a BC and IoT-based smart system to enhance the sustainability of prefabricated housing construction, integrating BIM to streamline the design and manufacturing process.
Li et al. (2022)	Researchers introduced a BC-Enabled IoT-BIM platform aimed at improving SCM in modular construction, leveraging BIM for real-time data exchange and coordination.
Kiu et al. (2022)	Researchers systematically reviewed the potential applications of BC in the construction industry, emphasizing the integration of BIM to enhance data integrity and project management.
Elghaish et al. (2023)	Researchers proposed a digitalized circular construction supply chain model that integrates BIM with BC technology to facilitate the reuse and recycling of building materials.
Brandín and Abrishami (2021)	Researchers discussed the use of BC-based technologies for information traceability across the asset data lifecycle, with BIM serving as a central platform for data management and collaboration.
Prakash and Ambekar (2020)	Researchers explored the digital transformation in the construction industry through BC technology, highlighting the role of BIM in achieving transparency and efficiency in project execution.

In summary, these studies collectively highlight the transformative impact of integrating BC and BIM in construction, focusing on sustainability, SCM, data integrity, and project management. They also explore digitalized circular supply chains and information traceability, emphasizing BIM's role in transparency and efficiency.

According to Figure 8, SC is the most trending tool in BIM. Additionally, sustainability, data analysis and management, off-site manufacturing, traceability, contract management, electronic document management, and funding management are discussed in terms of Industry 4.0. Figure 9 analyzes citations and journals interested in these issues: Journal of Cleaner Production has 108 citations, Journal of Construction Engineering and Management has 97, Automation in Construction has 49, and the International Journal of Construction Management has 41.

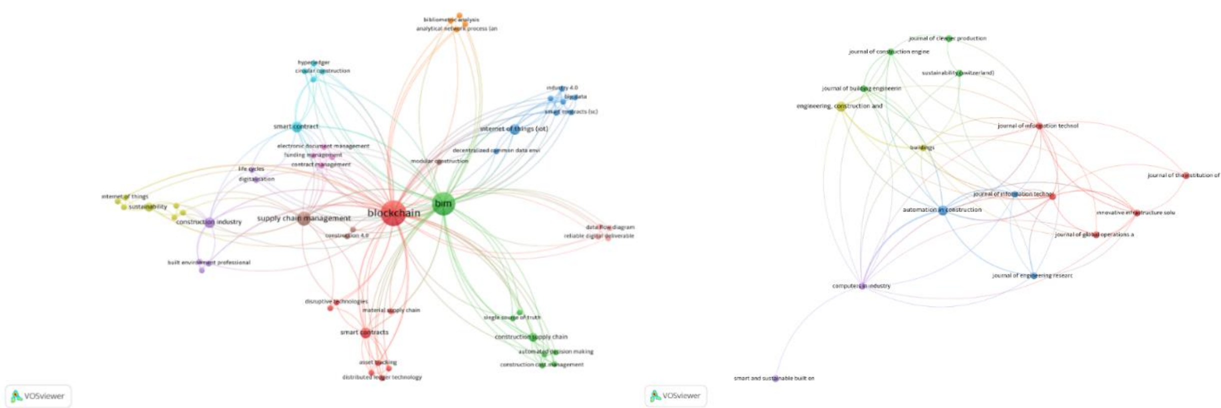


Figure 8 - 9: The science mapping of BC, SCM, construction and BIM related keywords & occurrence and The analyses of journal and citations BC, SCM, construction and BIM related keywords & occurrence by VOSviewer.

BC Integrated SCM in Construction & IoT: Recently, the construction industry has embraced IoT. This section explores pivotal research demonstrating IoT's transformative impact in construction, highlighting its role in enhancing productivity, safety, and decision-making through real-time data analysis. We analyzed 18 relevant studies, with the most cited contexts presented in Table 3 based on hierarchical citation.

Table 3. Most cited studies of BC, SCM, construction and IoT related keywords.

Sources	Context of Studies
Li et al. (2021)	They developed a smart system that combines BC with IoT to make building prefabricated homes more sustainable. It uses IoT for gathering data and BC for secure, transparent record-keeping.
Li et al. (2022)	The researchers created an IoT-BIM BC platform for better SCM in modular building. It uses IoT for easy data sharing and improving teamwork.

Hang & Kim (2021)	This study offers a way to improve BC networks to better support IoT, focusing on security and the ability to handle more users, especially for Hyperledger Fabric.
Elghaish et al. (2023)	The authors suggest a digital supply chain model that merges BIM and BC, with IoT helping to manage resources more efficiently in building projects.
Elghaish et al. (2022)	This study looks at Industry 4.0 technologies, with a focus on how IoT helps promote recycling and efficient use of resources in construction.
Elghaish et al. (2022)	This study discusses using BC for managing asset data over its lifetime, emphasizing how IoT ensures that data is traceable and accurate.
Xu et al. (2021)	This study introduces an intelligent BC scheme for SCM in manufacturing, highlighting how IoT improves decision-making and efficiency.

In summary, these studies highlight the significant impact of integrating IoT with BC and BIM technologies in revolutionizing the construction industry. This convergence enhances sustainability, streamlines SCM, and strengthens data integrity. The research also explores establishing a digitalized circular supply chain and fortifying information traceability, emphasizing IoT's pivotal role in transparency and operational efficiency within construction projects. This technological synergy fosters smarter, more responsive, and sustainable building practices.

According to Figure 10, SC is the most trending tool in IoT. Additionally, discussions around BIM, computer architecture, data interoperability, industrial internet, manufacturing, and data analysis and management are prevalent in Industry 4.0. Figure 11 analyzes citations and journals interested in these issues: Journal of Cleaner Production has 108 citations, Journal of Construction Engineering and Management has 97, BC: Research and Applications has 33, Automation in Construction has 32, Construction Innovation has 30, and Smart and Sustainable Built Environment has 27.

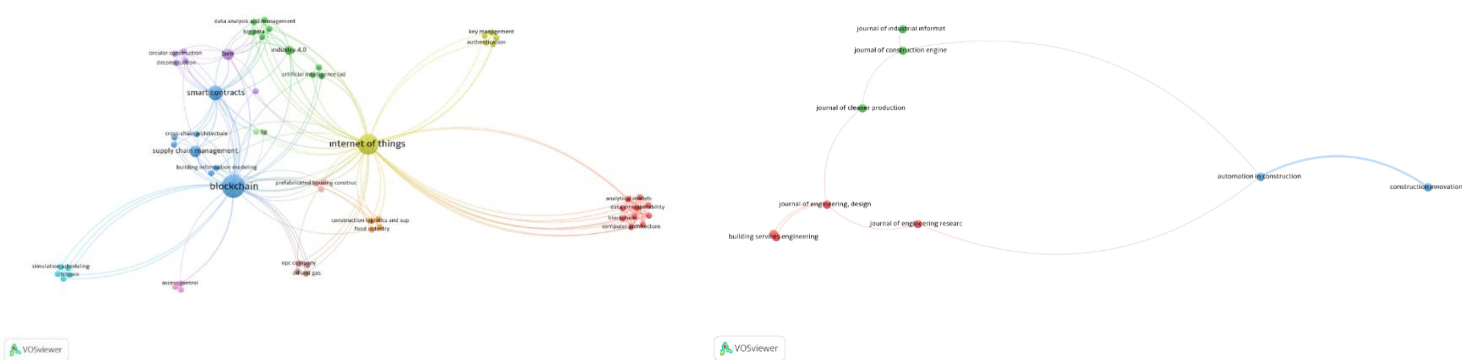


Figure 10 - 11: The science mapping of BC, SCM, construction and IoT related keywords & occurrence and the analyses of journal and citations BC, SCM, construction and IoT related keywords & occurrence by VOSviewer.

BC Integrated SCM in Construction & Traceability: In today's construction industry, traceability is gaining prominence. The focused studies illustrate how traceability is reshaping the sector, emphasizing its role in enhancing efficiency, safety, and decision-making quality through detailed tracking and data analysis. This transformation of traditional construction methods into transparent and reliable systems is evident. We analyzed 19 relevant studies, presenting the most cited contexts in Table 4 based on hierarchical citation.

Table 4. Most cited studies of BC, SCM, construction and traceability related keywords.

Sources	Context of Studies
Li et al. (2021)	They created a system using BC to track materials in precast construction, making sure every piece can be followed and accounted for.
Li et al. (2022)	This study introduces a system that combines BC, IoT, and BIM to keep tabs on materials in modular construction, ensuring everything is traceable from start to finish.
Hang & Kim (2021)	This study looks at how BC can be used to keep a close eye on the journey of fresh products, making sure they stay fresh and safe.
Elghaish et al. (2023)	This study explores how smart devices in construction can use BC to verify and track information, improving the way we keep track of construction materials.

In summary, these studies underscore the critical role of traceability in construction, facilitated by BC technology. They delve into enhancing traceability in SCM, particularly in precast and modular construction, ensuring transparency from production to placement. This focus aims to improve sustainability, data integrity, and project management while fostering a digitalized, circular supply chain that enhances accountability and efficiency in construction projects.

According to Figure 12, SC is the most trending tool in SCM. Additionally, discussions around IoT, sustainability, big data, BIM, offsite manufacturing, and automated decision-making are prevalent in Industry 4.0. Figure 13 analyzes citations and journals interested in these issues: Automation in Construction has 378 citations, Journal of Construction Engineering and Management has 97, and the International Journal of Production Research has 90.

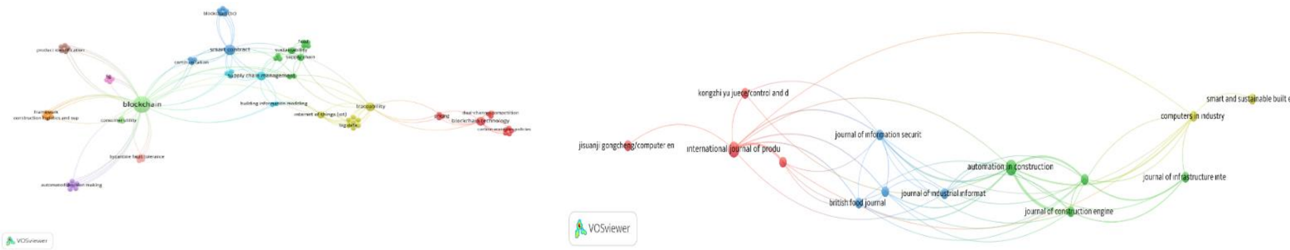


Figure 12 - 13: The science mapping of BC, SCM, construction and traceability related keywords & occurrence and the analyses of journal and citations BC, SCM, construction and traceability related keywords & occurrence by VOSviewer.

Discussion and Conclusion

Industry 4.0 has revolutionized various sectors through the convergence of technologies like BC, big data, AI, and IoT. However, the construction industry has been slower to adopt these innovations. This study explores how BC integrated SCM impacts construction, focusing on key aspects of Construction 4.0: SC, BIM, IoT, and traceability.

The research reveals that while BC integration in BIM, IoT, and traceability within construction SCM is still emerging, SC are gaining attention. Notably, contributions from China, the UK, and the USA stand out. The study emphasizes the potential of these digital tools to enhance transparency, efficiency, and collaboration in the construction industry.

In addition, the study identifies prominent journals that address these topics, such as Automation in Construction, Journal of Construction Engineering and Management, Journal of Cleaner Production, International Journal of Production Research etc.

BIM plays a pivotal role in this integration, addressing payment systems, asset lifecycle management, and project management. The synergy between BC, BIM, and IoT streamlines SCM, enhances sustainability, and ensures data integrity across construction projects.

Traceability is critical, especially in precast and modular construction, improving sustainability, data integrity, and project management. As Industry 4.0 evolves, the integration of BC, SCM, BIM, and IoT will shape a future of greater traceability, sustainability, and efficiency.

In summary, this transformative movement aligns with the broader objectives of Industry 4.0, with SC poised to play a dominant role in the near future.

References

Brandín, R., & Abrishami, S. (2021). Information traceability platforms for asset data lifecycle: blockchain-based technologies, *Smart and Sustainable Built Environment*, 10(3), 364-386.

Elghaish, F., Hosseini, M. R., Kocaturk, T., Arashpour, M., & Bararzadeh Ledari, M. (2023). Digitalised circular construction supply chain: an integrated BIM-Blockchain solution, *Automation in Construction*, 148, Article 104746.

Elghaish, F., Matarneh, S.T., Edwards, D.J., Pour Rahimian, F., El-Gohary, H., & Ejohwomu, O. (2022). Applications of Industry 4.0 digital technologies towards a construction circular economy: gap analysis and conceptual framework. *Construction Innovation,* 22(3), 647-670.

Gao, Z., Xu, L., Chen, L., Zhao, X., Lu, Y., & Shi, W. (2018). CoC: A Unified Distributed Ledger Based Supply Chain Management System. *Journal of Computer Science and Technology*, 33(2), 237-248.

Hamledari, H., & Fischer, M. (2021). Measuring the impact of blockchain and smart contracts on construction supply chain visibility. *Advanced Engineering Informatics*, 50, 101444.

Hamledari, H., & Fischer, M. (2021). The application of blockchain-based crypto assets for integrating the physical and financial supply chains in the construction & engineering industry. *Automation in Construction*, 127, 103711.

Hang, L., & Kim, D.-H. (2021). Optimal blockchain network construction methodology based on analysis of configurable components for enhancing Hyperledger Fabric performance. *Blockchain: Research and Applications*, 2(1), 100009.

Hewavitharana, B., Nanayakkara, S., & Perera, S. (2019). Enhancing supply chain management in construction: The role of blockchain technology. *Journal of Sustainable Construction Materials and Technologies,* 3(3), 217-225.

Karasözen, B., Bayram, Ö., & Zan, B. U. (2021). Comparison of WoS and Scopus Databases. *DergiPark*.

Kifokeris, D., & Koch, C. (2020). A conceptual digital business model for construction logistics consultants, featuring a sociomaterial blockchain solution for integrated economic, material and information flows. *Journal of Information Technology in Construction*, 25, 500-521.

Kiu, M.S., Chia, F.C., & Wong, P.F. (2022). Exploring the potentials of blockchain application in construction industry: a systematic review. *International Journal of Construction Management*, 22(15), 2931-2940.

Kshetri, N. (2021). Evolving uses of artificial intelligence in human resource management in emerging economies in the Global South: some preliminary evidence. *Management Research Review*, 44(7), 970-990.

Li, C. Z., Chen, Z., Xue, F., Kong, X.T.R., Xiao, B., Lai, X., & Zhao, Y. (2021). A blockchain- and IoT-based smart product-service system for the sustainability of prefabricated housing construction, *Journal of Cleaner Production*, Article ID 125391.

Li, X., Lu, W., Xue, F., Wu, L., Zhao, R., Lou, J., & Xu, J. (2022). Blockchain-Enabled IoT-BIM Platform for Supply Chain Management in Modular Construction, *Journal of Construction Engineering and Management*, 148(2), 0002229.

Liu, Y., & Li, X. (2023). How to promote the application of blockchain in prefabricated building supply chain? Analysis based on evolutionary game. *Canadian Journal of Civil Engineering*, 50(8), 645-658. doi:10.1139/cjce-2022-0245

Liu, Y., Chi, C., Zhang, Y., & Tang, T. (2022). Identification and Resolution for Industrial Internet: Architecture and Key Technology. *IEEE Internet of Things Journal*, 20.

Lu, W., Li, X., Xue, F., Zhao, R., Wu, L., & Yeh, A.G.O. (2021). Exploring smart construction objects as blockchain oracles in construction supply chain management. *Automation in Construction*, 129, 103816.

Nanayakkara, S., Perera, S., Senaratne, S., Weerasuriya, G. T., & Bandara, H. M. N. D. (2021). Blockchain and smart contracts: a solution for payment issues in construction supply chains, *Informatics*, 8(2), 36.

Pech, M., & Vrchota, J. (2022). The Product Customization Process in Relation to Industry 4.0 and Digitalization. *Processes*, 10(3), 539. 1

Petersen, P. C., et al. (2021). CellExplorer: A framework for visualizing and characterizing single neurons. *Neuron*, 109(11), 3594–3608. 27

Prakash, A., & Ambekar, S. (2020). Digital transformation using blockchain technology in the construction industry, *Journal of Information Technology Case and Application Research*, 22(4), 256–278.

Qian, X., & Papadonikolaki, E. (2021). Shifting trust in construction supply chains through blockchain technology. *Engineering, Construction and Architectural Management*, 28(2), 584-602.

Rainero, C., & Modarelli, G. (2021). Food tracking and blockchain-induced knowledge: a corporate social responsibility tool for sustainable decision-making. *British Food Journal*, 123(12), 4284-4308.

Rodrigo, M.N.N., Perera, S., Senaratne, S., & Jin, X. (2020). Potential application of blockchain technology for embodied carbon estimating in construction supply chains. *Buildings*, 10(8), 140.

Sivula, A., Shamsuzzoha, A., & Helo, P. (2021). Requirements for blockchain technology in supply chain management: An exploratory case study. *Operations and Supply Chain Management*, 14(1), 39-50.

Tezel, A., Febrero, P., Papadonikolaki, E., & Yitmen, I. (2021). Insights into Blockchain Implementation in Construction: Models for Supply Chain Management. *Journal of Management in Engineering*, 37(4).

Tezel, A., Papadonikolaki, E., Yitmen, I., & Hilletofth, P. (2020). Preparing construction supply chains for blockchain technology: An investigation of its potential and future directions, *Frontiers of Engineering Management*, 7, 547-563.

Wan, P.K., Huang, L., & Holtskog, H. (2020). Blockchain-Enabled Information Sharing within a Supply Chain: A Systematic Literature Review. *IEEE Access*, 8, 9032112.

Wang, E. K., Park, M. S., Kim, K., & Kim, K. J. (2021). Blockchain-Based Automatic Tracking and Extracting Construction Document for Claim and Dispute Support. *KSCE Journal of Civil Engineering*, 26, 3707-3724.

Wang, Y., Chen, C.H., & Zghari-Sales, A. (2021). Designing a blockchain enabled supply chain. *International Journal of Production Research*, 59(5), 1450-1475.

Wang, Z., Wang, T., Hu, H., Gong, J., Ren, X., & Xiao, Q. (2020). Blockchain-based framework for improving supply chain traceability and information sharing in precast construction. *Automation in Construction*, 111, 103063.

Wu, X.-Y., Fan, Z.-P., & Cao, B.-B. (2023). An analysis of strategies for adopting blockchain technology in the fresh product supply chain. *International Journal of Production Research*, 61(11), 3717-3734.

Wu, H., Zhang, P., Li, H., & Luo, X. (2022). Blockchain Technology in the Construction Industry: Current Status, Challenges, and Future Directions. *Journal of Construction Engineering and Management*, 148(10), 03122007.

Xiong, F., Xiao, R., Ren, W., Zheng, R., & Jiang, J. (2019). A key protection scheme based on secret sharing for blockchain-based construction supply chain system, *IEEE Access*, 7, 8815705.

Xu, Z., Zhang, J., Song, Z., Liu, Y., Li, J., & Zhou, J. (2021). A scheme for intelligent blockchain-based manufacturing industry supply chain management. *Computing*, 103, 1771-1790.

Bibliometric Analysis of Relational Contracting in Collaborative Construction Projects

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Abstract

As a key driver of global economic growth, the construction industry accounts for 13% of the world economy and spends around $10 trillion annually. To succeed in this competitive industry, companies must innovate products, materials and delivery systems. Technological advances and project complexities require flexible relationships between multiple stakeholders. While traditional bilateral agreements are often challenged, standard multilateral agreements face cultural challenges. In addition, over-specification of contracts can lead to trust and communication problems. In multi-participant collaborative construction projects, in addition to the elaboration of contracts, stakeholders' goodwill, belief in the success of the project, willingness to work together, information sharing, and communication should be strengthened by a relational contract. The aim of the study is to enhance collaboration, promote stakeholder alignment, improve project performance, reduce disputes and achieve sustainability goals in construction projects by utilizing relational contracts. For this purpose, the SCOPUS database was searched using 12 keywords related to relational contracts. The identified studies were mapped through bibliometric analysis using VOSviewer to map the concepts potentially related to relational contracts in the literature. The resulting maps are classified according to potentially related clusters to comprehensively perceive and use relational contracts. The analysis highlights the different dimensions of relational contracts and reveals the links between trust and organizational commitment as well as project speed and quality. The psychological contract concept is linked to construction projects and change management, suggesting potential benefits for the construction industry. Keywords such as "transaction cost" and "procurement" align with broader concepts such as agency theory and teamwork, and illustrate how relational terms can lead to financial gains. Overall, integrating relational concepts into contracts can improve project performance and minimize disputes more effectively than relying solely on rigid and penalizing contract structures.

Keywords: *bibliometric analysis, collaborative construction, framework contract, relational contracting, VOSviewer.*

Introduction

The rapid advancement of technology and construction methods has led to an increase in the complexity of construction projects. As many stakeholders need to collaborate throughout the building's lifecycle, it is critical to establish adaptable, healthy, and long-lasting linkages between these stakeholders. Traditional bilateral agreements are inadequate to handle these complex relationships involving multiple stakeholders. Standard multilateral agreements are not suitable for all cultures and societies, making them difficult for stakeholders to accept. Trying to be as detailed as possible in agreements and defining roles and responsibilities is one way to reduce disputes in complex project processes. However, this effort undermines stakeholder trust and has a detrimental impact on communication and information exchange.

Classical contract theory assumes that comprehensive agreements that contain all required safeguards against opportunistic behavior and transaction uncertainty can be drafted (Zheng et al., 2008). Furthermore, traditional contracts usually assign obligations, minimize risk through risk reduction and mitigation strategies, and attempt to cover every potential scenario. Transactional contracting approach aims to control behaviors as well as hazards and their effects (Galvin et al., 2021; Nwajei, 2021). Moreover, there is a notion that the more contractual terms or conditions there are, the better, and collaborative construction project management incorporates contractual components that promote cooperation (Engebø et al., 2020). However, in accordance with multiple studies, contracts are often incomplete in practice because of various factors like asymmetric information, costs associated with contract preparation, incapacity to anticipate all contingencies, etc. (Memon et al., 2015; Rahman & Kumaraswamy, 2004, Jobidon et al., 2019; Ning & Ling, 2014; Zheng et al., 2008).

According to Harper et al. (2016), promises form the basis of contracts. They occur when two parties agree that one will provide a good or service to the other and the other will pay the first party for the good or service. The agreement between the parties is what constitutes their contract. Written contracts, although oral in nature, have replaced oral contracts because of the practical difficulties associated with honoring commitments. Documenting and outlining the terms and conditions of an agreement through written contracts is a more reliable and enforceable method (IIiff et al., 2012). It should be highlighted, therefore, that a legal contract's written responsibilities and duties might not always be met (Cho & Hadikusumo, 2023). As a result, informal agreements must be included to such contracts (Macneil, 1980). In addition to being based on verbal agreements and other types of commitments made by the parties, responsibilities can also be stated in a legally binding contract (Koh et al., 2004). When a project begins, the parties involved anticipate reciprocal dedication and a sharing of responsibility. However, because of knowledge asymmetry, they might attempt to maximize their own interests during the project (Forsythe et al., 2015). When one party to a contractual agreement has more knowledge about specifics of the exchange of money and services than the other party or parties, information asymmetry arises, allowing one side to take advantage of the other.

In addition to contract specification, a relational contract should reinforce stakeholders' goodwill, belief in project success, cooperation, communication, information sharing and willingness to cooperate, communicate and share information in multilateral collaborative construction projects. The achievement of truly integrated project management depends on the willingness of stakeholders to cooperate and believe in the success of the project. This paper therefore aims to identify, through a bibliometric analysis, the ways in which relational contracts have been addressed in recent academic studies. Due to the large number of studies focusing on the topic in the SCOPUS database, VOSviewer, a software tool for creating and displaying bibliometric maps, was used to analyse existing research. In this way, a search path will be created for future studies on relational contracts.

Data Collection and Findings

The research design principles were developed following the ongoing literature review conducted as part of the thesis research. The stages of the schematic literature review were identified and the protocol to be followed was specified. The parameters of the literature review are shown in the flowchart. In this context, the SCOPUS database was searched through TITLE, ABSTRACT & KEYWORDS. In the research, 12 keywords related to relational framework contracting were searched. These keywords are:

"relational contract"	"partnering contract"
"relational contracting"	"partnering contracting"
"collaborative contract"	"framework contract"
"collaborative contracting"	"framework contracting"
"alliance contract"	"IPD contract"
"alliance contracting"	"IPD contracting"

The flow chart and parameters of the bibliometric analysis are shown in Figure 1 below.

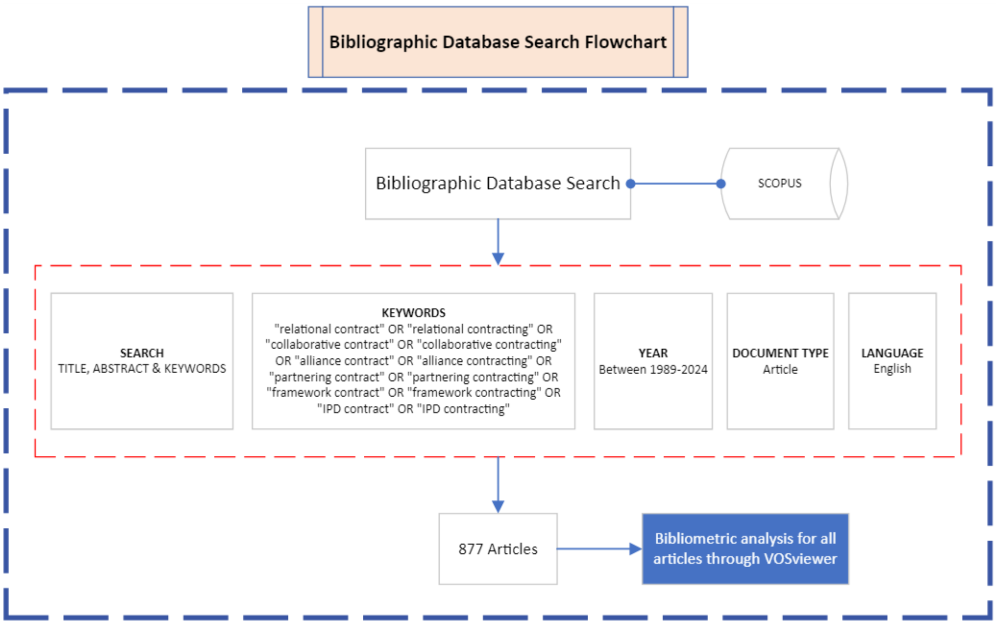

Figure 1: Flow chart and parameters of bibliometric analysis.

As a result of the search, 877 peer-reviewed articles in English between 1989 and 2024 were found. Bibliometric analysis of 877 articles found as a result of the search was conducted. The figure below (Figure 2) shows the distribution of articles containing the searched keywords by year. We can say that the number of articles increased from 1989 to the beginning of 2024 (carried out on 15 March 2024). This shows us that researchers' interest in the keywords we searched for has increased.

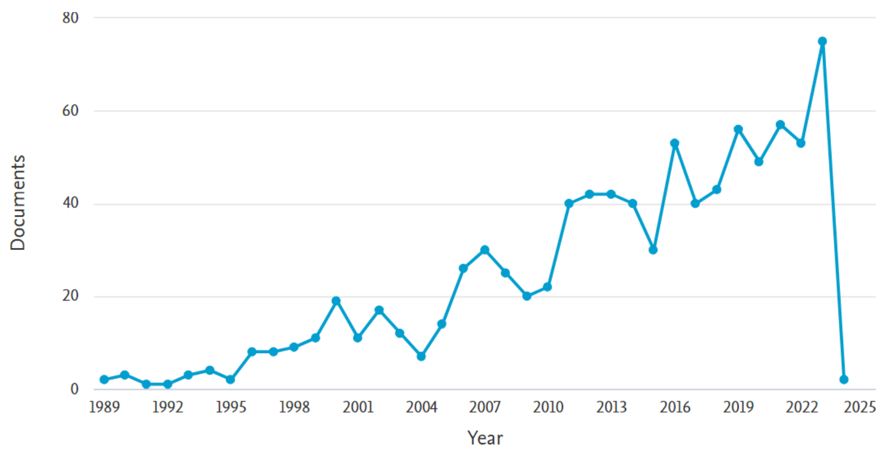

Figure 2: Documents distribution by year (From 1989 to 2024).

The figure below (Figure 3) shows in which scientific fields the searched keywords are researched. The first 4 research areas, with a total share of up to 80%, can be directly related to the construction industry.

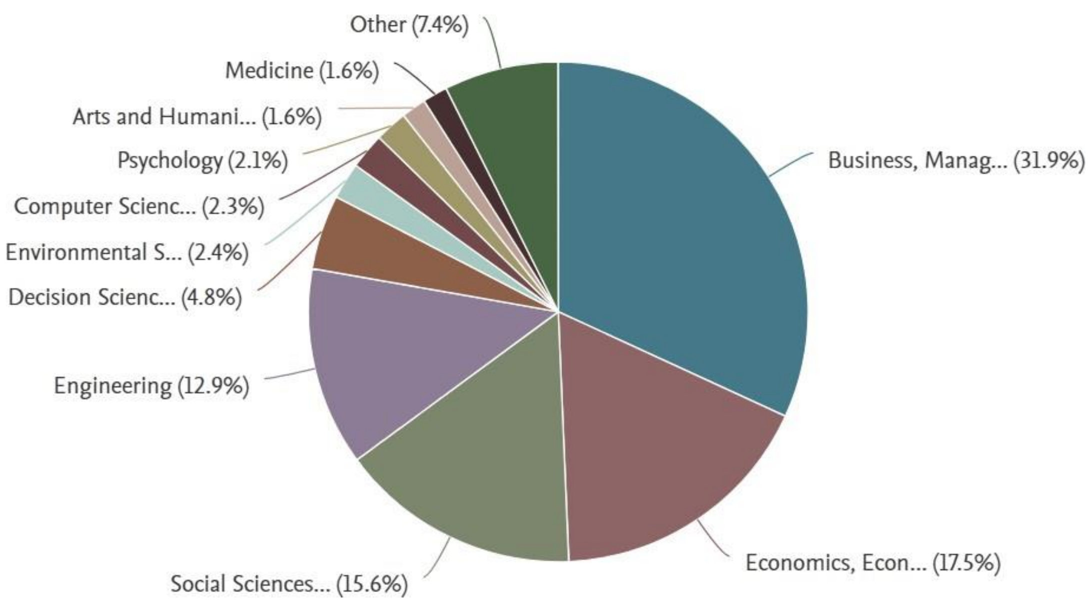

Figure 3: Distribution of studies according to research areas.

Setting the minimum number of articles published in one country as 3 and the minimum number of citations as 20 (Jin et al., 2018), 38 out of the 83 countries meet the threshold standard and are retained. Figure 4 shows the distribution of the number of studies containing the searched keywords, the number of citations these studies received, and the relationships between the studies by country. The countries in the table are ranked in descending order according to the number of articles. Accordingly, United States is the leading country in both the number of studies and the number of citations. Turkey comes towards the bottom of the list with 6 studies on the number of studies containing the searched keywords. This situation leads to the conclusion that there is a significant need for research on this subject area.

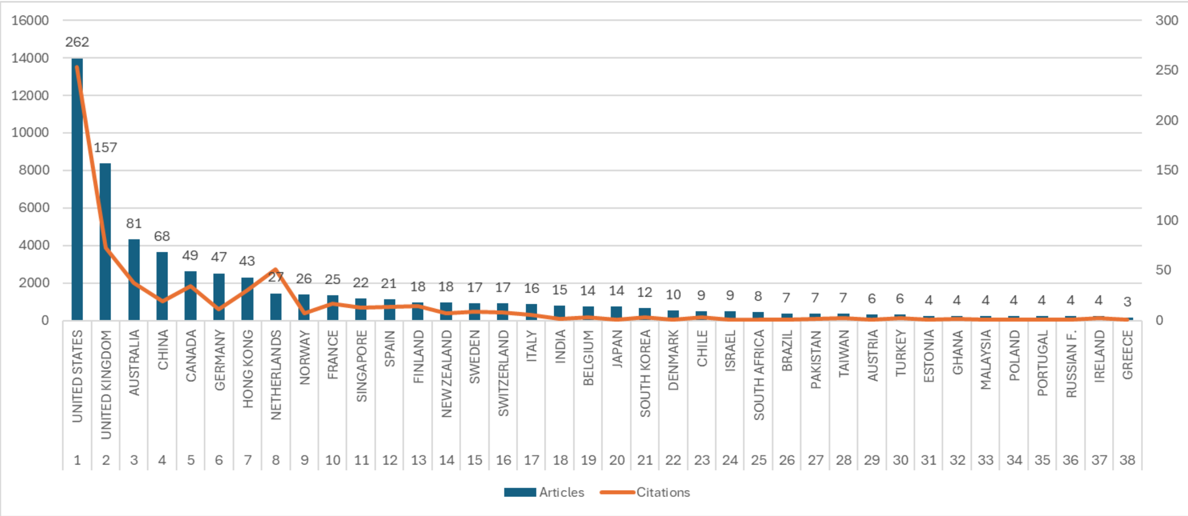

Figure 4: Ranking of the studies by country.

Figure 5 below shows the relationship between research in countries and research in other countries. According to the figure, the United States is the mainstays of current development in relational contracting. Australia, China and United Kingdom follow as the other most important countries hosting research.

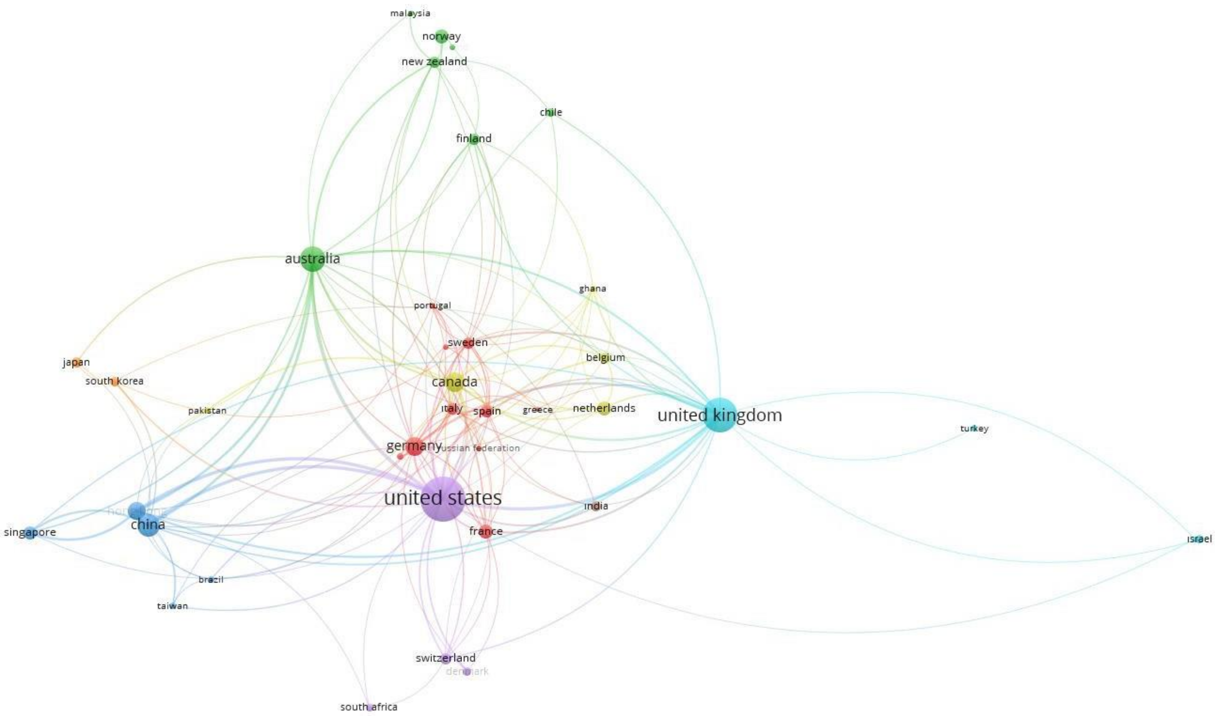

Figure 5: Ranking of the studies by country.

Keyword co-occurance analysis was conducted for 877 articles in the study. The minimum co-occurrence time of keywords is set to 3 (Liu et al., 2020; Jin et al., 2018). Therefore, 172 of all the 2073 keywords meeting the preset minimum threshold were screened. Finally, synonymous keywords were merged, such as:

- “relational contracts”, “relational contract” to “relational contracting”
- “integrated project delivery (ipd)” to “integrated project delivery”
- “partnership” to “partnering”
- “project alliance” and “alliance contract” to “alliance contracting”

As a result, 166 valid keywords are retained, and the scientific map for visual analysis is obtained. Figure 6 below illustrates the visual relationship analysis of these keywords.

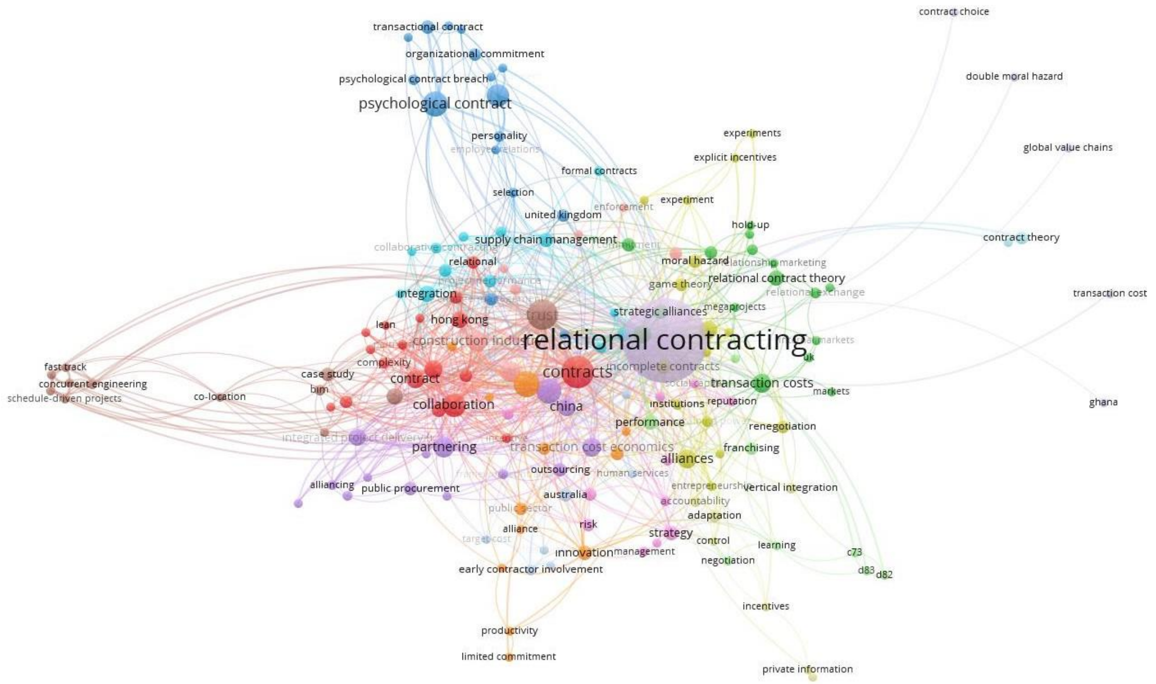

Figure 6: The holistic map as a result of co-occurrence analysis in VOSviewer.

The following figure (Figure 7) shows the occurrence of the identified 166 keywords over time. According to the figure, as the colors change from blue to yellow, the use of the keyword becomes more up to date. The figure shows that, in alphabetical order, the most recent terms associated with the relational contract are as follows:
Adaptation; Bargainin power; BIM; Block chain; Construction project management; Construction projects; Global value chains; Incentives; Infrastructure; Lean construction; Mega project; Private information; Procurement; Project performance; Reciprocity; Relational contract theory; Relational governance; Sustainability; Transaction cost; Turnover intention.

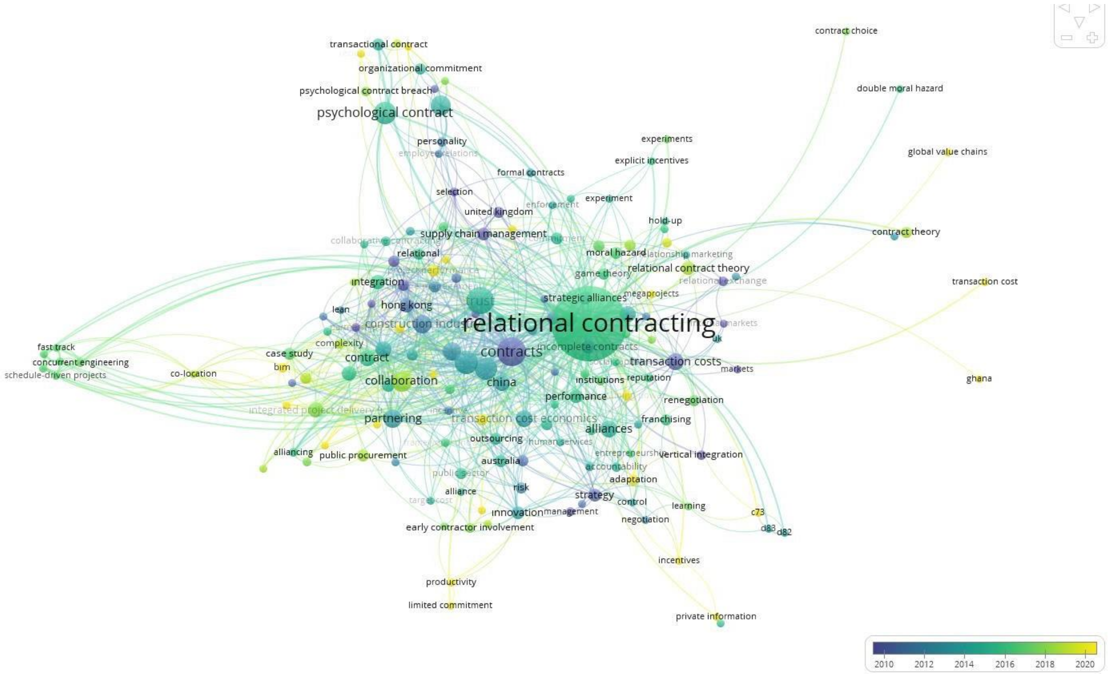

Figure 7: The holistic map as a result of co-occurrence analysis in VOSviewer.

When we examine Figure 6 and Figure 7 above, the titles Trust, Psychological Contract, Procurement, Transaction Costs have emerged as the most recurring words after the 12 keywords used in the research. These words also appear in relatively new studies (Figure 7). The fact that the words Trust and Psychological Contract are repeated so many times, in line with the literature, tells us that people's character, commitment, soft skills and human relations are important in relational contracts. In addition, the fact that Procurement and Transaction Cost are other prominent keywords reveals that the financial dimension of relational contracts and supply chain management are also important. The relational contracting approach emphasizes the belief in the success of the project and the proportionate sharing of the returns from the final product, this human-centered and realistic approach helps to reduce conflicts in projects. The graph 8 below shows the clusters of the 4 keywords mentioned. When we examine these clusters, it is understood that for the relational contracting approach to be successful, the focus should be very comprehensive, emphasizing both tangible and intangible aspects.

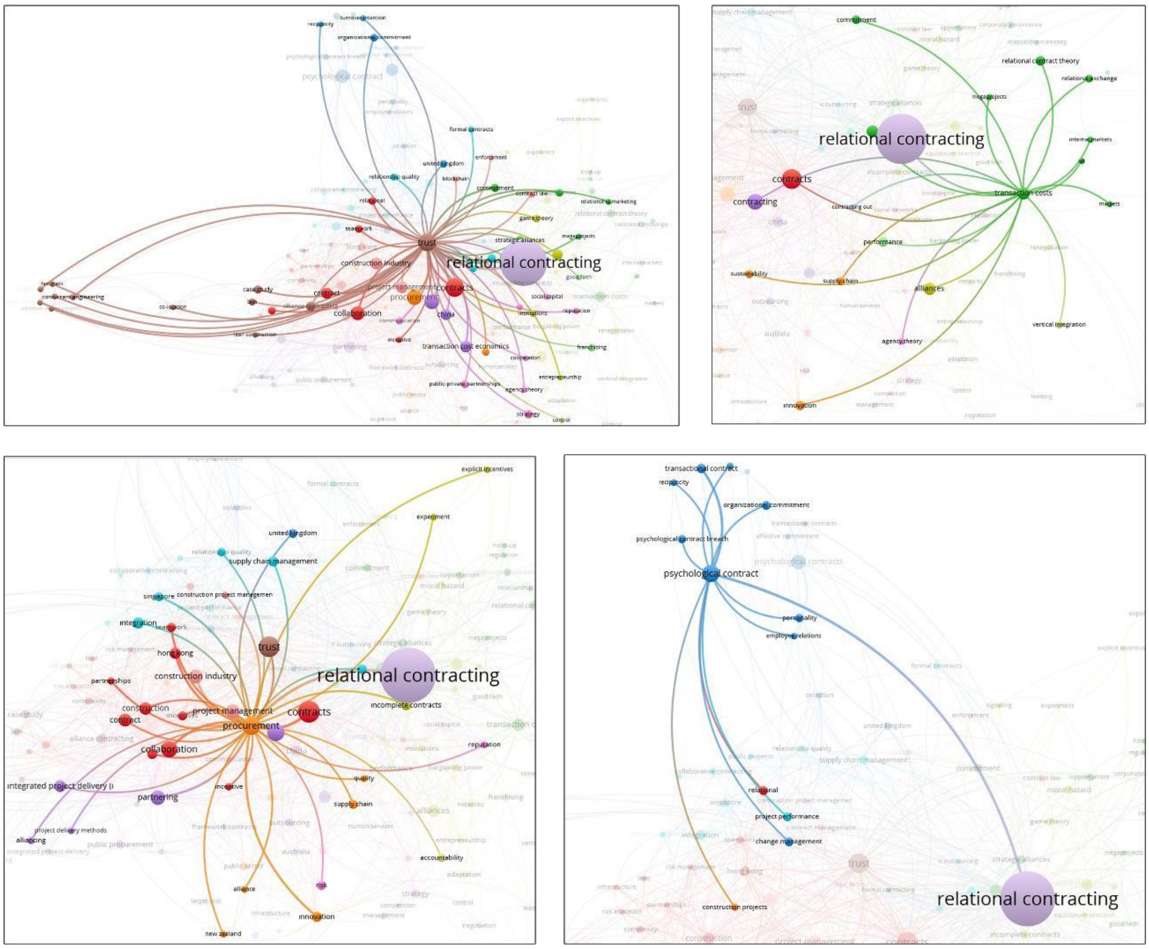

Figure 8: Clusters for the words Trust, Transaction Cost, Procurement and Psychological Contract respectively.

Conclusion

The aim of this study is to use the VOSviewer program to create a comprehensive map showing research topics and gaps related to relational and collaborative contracts in the construction industry. Graphs from Scopus are also used to illustrate the current state of research in the construction industry. In the context of relational contracts and the construction industry, the co-occurrence keyword analysis performed in this study can help to clarify concerns. It also helps to point out areas of interest that scholars have not yet explored. Given the volume and diversity of publications, more research and learning is needed to fully understand the relational contracts and construction industry context.

When we examine the 4 most repeated words after the 12 keywords under their clusters (Figure 8), it is seen that there are many tangible and intangible dimensions of relational contracts. When the keyword “Trust” is considered, it is seen that it is highly related to character traits such as organizational commitment, relationship quality and reciprocity, as well as keywords that define project speed and quality such as fast track, project acceleration, design-construction, concurrent engineering. Similarly, the concept of “Psychological Contract” is also related to concepts such as construction projects, project performance and change management, and we can conclude that it can make strong contributions to the construction industry.

Moreover, although the keyword "transactional cost" has a financial equivalent, it is related to collective concepts such as vertical integration, agency theory, commitment, etc., which may indicate that relational terms can turn into financial gains. In the same way, the fact that the keyword "procurement" is related to concepts such as incentives, reputation, incomplete contracts, teamwork, etc. may guide us on the necessity of looking at the procurement process from the perspective of relational contracts. The fact that concepts from different fields of study have strong interrelationships demonstrates that the way to improve project performance and reduce disputation is not only by making contracts more rigid, detailed and punishment based, but perhaps by incorporating relational concepts into the contract.

Finally, 877 articles found as a result of the keyword search proceeded to the next stage for abstract reading. The abstracts of these 877 articles were read and 270 articles that could be associated with the construction sector were found. A detailed analysis of the 270 articles will be carried out in the next stages of the research.

References

Cho, W. M., & Hadikusumo, B. H. W. (2023). Psychological contract between contractors and owners in construction projects: The mediating role of inter-organisational teamwork, *Engineering, Construction and Architectural Management*, *Vol. ahead-of-print*, No. ahead-of-print. https://doi.org/10.1108/ECAM-11-2022-1099

Engebø, A., Lædre, O., Young, B., Larssen, P. F., Lohne, J., & Klakegg, O. J. (2020). Collaborative project delivery methods: A scoping review. *Journal of Civil Engineering and Management*, *26*(3), 278–303. https://doi.org/10.3846/jcem.2020.12186

Forsythe, P., Sankaran, S., & Biesenthal, C. (2015). How far can BIM reduce information asymmetry in the Australian construction context? *Project Management Journal*, *46*(3), 75–87. https://doi.org/10.1002/pmj.21504

Galvin, P., Tywoniak, S., & Sutherland, J. (2021). Collaboration and opportunism in megaproject alliance contracts: The interplay between governance, trust and culture. *International Journal of Project Management*, *39*(4), 394–405. https://doi.org/10.1016/j.ijproman.2021.02.007

Harper, C. M., Molenaar, K. R., & Cannon, J. P. (2016). Measuring constructs of relational contracting in construction projects: The owner's perspective. *Journal of Construction Engineering and Management*, *142*(10). https://doi.org/10.1061/(asce)co.1943-7862.0001169

IIiff, B. A., Halls, P., & Tedjeske, J. (2012). The shifting sands of contract drafting, interpretation, and application, *Construction Law*, *32*(2), 1-11.

Jin, R., Gao, S., Cheshmehzangi, A., & Aboagye-Nimo, E. (2018). A holistic review of off- site construction literature published between 2008 and 2018. *Journal of Cleaner Production*, *202*, 1202-1219.

Jobidon, G., Lemieux, P., & Beauregard, R. (2019). Comparison of Quebec's project delivery methods: Contractual language. *Laws*, *2019*, 75.

Koh, C., Ang, S., & Straub, D. W. (2004). IT outsourcing success: A psychological contract perspective, *Information Systems Research*, *15*(4), 356-373.

Kumaraswamy, M., Rahman, M., Ling, F., & Phng, S. (2005). Reconstructing cultures for relational contracting. *Journal of Construction Engineering and Management, 131*(10), 1065–1075.

Liu, Y., Dong, J., & Shen, L. (2020). A conceptual development framework for prefabricated construction supply chain management: An integrated overview. *Sustainability*, *12*(5), 1878.

Macneil, I. R. (1980). The new social contract: An inquiry into modern contractual relations. *Yale University Press*, New Haven.

Memon, S. A., Hadikusumo, B. H. W., & Sunindijo, R. Y. (2015). Using social interaction theory to promote successful relational contracting between clients and contractors in construction. *Journal of Management in Engineering*, *31*(6), 1–7. https://doi.org/10.1061/(asce)me.1943-5479.0000344

Ning, Y., Yng Ling, F. Y. (2014). Boosting public construction project outcomes through relational transactions. *Journal of Construction Engineering and Management. 140*(1), 04013037.

Nwajei, U. O. K. (2021). How relational contract theory influence management strategies and project outcomes: a systematic literature review. *Construction Management and Economics*, *39*(5), 432–457. https://doi.org/10.1080/01446193.2021.1913285

Zheng, J., Roehrich, J. K., & Lewis, M. A. (2008). The dynamics of contractual and relational governance: Evidence from long-term public-private procurement arrangements. *Journal of Purchasing and Supply Management*, *14*(1), 43–54. https://doi.org/10.1016/j.pursup.2008.01.004

From People to Projects: A Perspective on Social Factors Impacting BIM Adoption

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Abstract

In recent years, the construction industry has witnessed a significant surge in the adoption of Building Information Modelling (BIM), raising concerns regarding the potential risks and challenges that accompany its rapid expansion. Identifying and addressing such challenges in BIM projects is crucial to mitigate disputes and avoid financial and time-related setbacks. However, there exists a notable gap in understanding how to navigate these challenges.

This article delves into the social challenges linked to the adoption of BIM in the industry, focusing on the role of project stakeholders. By scrutinizing the root causes of existing risks and challenges associated with BIM, the research aims to highlight the key social obstacles impacting widespread BIM adoption.

The study, which draws insights from in-depth interviews with 19 European experts, primarily professional consultants, underscores the influential role of human factors in the implementation of BIM. It explores how social behaviours impact the widespread adoption of BIM in the industry. The overarching objective of this paper is to pinpoint potential challenges associated with social factors in BIM projects and suggest more effective strategies for addressing them.

The research proposes improved practices that empower stakeholders to handle BIM-related risks and challenges more effectively. The ultimate goal is to enhance the success of BIM projects by offering practical solutions for addressing the complexities associated with social factors in the industry.

Keywords: *building information modeling (BIM), social challenges, socio-technical factors, socio-organizational factors*

Introduction

Building Information Modeling (BIM) has been recognized as a transformative technology in the Architecture, Engineering, and Construction (AEC) industry, enhancing collaboration and efficiency in construction projects (Oesterreich & Teuteberg, 2019). Despite its potential, the widespread adoption of BIM has encountered significant challenges, often arising from social factors such as organizational culture, team dynamics, and resistance to change (Blay et al., 2019; Raja Mohd Noor et al., 2023). BIM platforms are regarded as socio-technical systems, integrating technical and social components that influence organizational structures (Blay et al., 2019; Raja Mohd Noor et al., 2023). Technical components include the tools and systems supporting BIM, while social components involve organizational structures, team collaboration, and interpersonal interactions (Sackey et al., 2015).

While technical issues have been extensively addressed, the social aspects of BIM adoption remain relatively underexplored (Alreshidi et al., 2017). BIM is perceived as a holistic system where technology alone is insufficient, and social acceptance is crucial for effective implementation (Olofsson Hallén et al., 2023). Despite the importance of social aspects, few studies explicitly focus on them (Olofsson Hallén et al., 2023; Alreshidi et al., 2017). The context of social collaboration in BIM remains under-investigated, highlighting a literature gap (Raja Mohd Noor et al., 2023). Addressing social challenges and fostering effective collaboration among BIM stakeholders are critical areas for research and practice. This paper examines the social factors and challenges affecting BIM adoption in the AEC industry. By exploring the interaction between technical and social components, the study seeks to understand the reasons behind the slow adoption of BIM and to identify strategies for improving collaboration and project outcomes. This research aims to address the gap in the literature regarding the influence of social components on BIM adoption and implementation.

Literature Review

The integration of BIM into construction projects has revealed the BIM technology's role as a socio-technical system within organizational structures, with social and technical components that are deeply intertwined (Blay et al., 2019; Raja Mohd Noor et al., 2023). While the technical aspects of BIM often receive the most attention, the social components, which encompass organizational knowledge, skills, values, and structural systems, play a crucial role in determining the success of BIM adoption and collaboration (Sackey et al., 2015; Alreshidi et al., 2017). Mignone et al. (2016) emphasized that social-technical components are essential for effective organizational collaboration, noting that the quality of interactions among multi-actor teams can significantly impact project outcomes (Mignone et al., 2016). Despite the emphasis on technical elements, research indicates that the social dimensions are critical in ensuring the effectiveness of BIM collaboration (Blay et al., 2019). The changing dynamics of roles among multiple actors collaborating in a BIM environment, and the restructuring of contractual and organizational relationships are among the factors that can enhance social collaboration (Faris et al., 2022; Mignone et al., 2016).

Despite the apparent benefits of BIM, its implementation is often slow due to various social and organizational challenges (Blay et al., 2019; Merschbrock & Munkvold, 2015). A recent study by the UK for Digital Build Britain highlighted the importance of focusing on the social components of BIM collaboration to ensure the success of BIM projects (Blay et al., 2019). This aligns with the notion that social collaboration among multi-actor teams is crucial for positive project outcomes (Raja Mohd Noor et al., 2023).

Sackey et al. (2015) analyzed intraorganizational interests through the Leavitt socio-technical model, identifying four synergistic components for achieving sociotechnical balance, namely: actor, structure, task, and technology (Sackey et al., 2015). In the context of BIM-based collaboration, human interaction and organizational processes (social components) are considered fundamental to managing project activities (Merschbrock et al., 2018). Adamu et al. (2015) suggested that it is people, not technology, that drive collaboration and influence BIM operation (Adamu et al., 2015). Blay et al. (2019) supported this view, stressing that changes in actors' roles, contractual relationships, and organizational structures promote social collaboration. Additionally, challenges in the BIM adoption process may be related to the broader socio-organizational context, where factors like resistance to change, lack of social infrastructure, and inadequate training contribute to slow adoption rates (Gamil & Rahman, 2019; Oesterreich & Teuteberg, 2019). Furthermore, Rogers' (1995) framework for innovation adoption identifies three types of decisions: optional, collective, and authority (Rogers, 1995). In the construction context, authority decisions are typically used to adopt BIM, where project owners or managers make the decisions, but resistance to change at the user level can complicate implementation (Cao et al., 2015).

Research Methods

This study utilizes content analysis of qualitative data collected through semi-structured interviews with BIM experts in the AEC industry. These interviews were conducted to examine the prevailing risks and challenges in BIM implementation. Pilot interviews were initially conducted to refine the interview questions. The sample size was determined by achieving theoretical saturation.

Interviewees were predominantly identified via snowball sampling, using personal networks and BIM associations. Participants were selected based on their extensive BIM project experience or involvement in BIM legal cases. Demographically, 75% of interviewees had over ten years of experience, with 65% having more than fifteen years, and none having less than five years. Approximately half of the participants had backgrounds in design, 35% were from construction, and 15% were construction lawyers.

Findings and Discussions

Content analysis of the gathered data revealed nine major emerging social factors that are affecting BIM adoption in the industry. These social factors are elaborated in detail in the following sections.

BIM Attitude Across Generations
The interview findings highlight that the main obstacle to BIM adoption is perceived to lie in people and their attitudes, with this factor seemingly correlated with the age of the participants. Resistance to new technologies like BIM, particularly evident among many traditional companies in the industry, contributes to friction in the transition process. Younger generations exhibit greater willingness to embrace BIM, while older companies encounter difficulties in adaptation. It is suggested that proper training and clear agreements may facilitate smoother adoption of BIM. However, willingness to undertake BIM training is also correlated with the age of the users. This issue is also highlighted by (Ullah et al., 2022) regarding training and learning process that pertains to age, with older employees potentially displaying less interest in acquiring new technological skills (Ullah et al., 2022). Similarly, Wang et al. (2020) argue that empirical findings suggest age, as an individual-level characteristic, is positively associated with behavioral resistance to BIM implementation (Wang et al., 2020).

Silverio et al. (2023) argue that the perceived complexity of innovation within a social system negatively impacts its adoption rate, with BIM often depicted as a complex process, and software seen as overly intricate and a barrier to wider adoption (Silverio et al., 2023). Consequently, some organizations refrain from implementing BIM due to concerns about complexity and challenges in understanding and implementing BIM software.

Experience

The interview findings demonstrate that the definition of BIM can exhibit variability, leading to conflicts among stakeholders. While some clients anticipate using BIM, the actual implementation may not align with their expectations. Based on the interview results, the specialists from government parties, do not generally possess high levels of experience with BIM. Nonetheless, clients retain the option to engage BIM consultants, although encountering challenges in finding experts with comprehensive awareness and knowledge of BIM. This observation is supported by Silverio et al. (2023), who assert that BIM has not been a prerequisite among supply chain members in the Dominican Republic, with many designers lacking BIM proficiency, contributing to a shortage of skilled professionals in building information modeling within the country. Consequently, some organizations encounter difficulties in recruiting BIM-skilled individuals due to the scarcity of local BIM professionals (Silverio et al., 2023).

The findings recommend commencing with smaller BIM projects to gradually accumulate experience, as tackling large projects without prior experience may lead to failure. Some interviewees clarify that defining the BIM implementation process necessitates foreseeing all aspects, yet the shortage of training and experience may hinder the accurate determination of future needs. In this regard, Olofsson Hallén et al. (2023) argue that increased experience generally bring about a greater awareness of potential BIM benefits, with BIM experience constituting a significant factor in realizing these benefits. Contractors with more years of BIM experience are inclined to apply BIM in complex construction projects (Olofsson Hallén et al., 2023).

Resistance to Change

The interview findings underscore that the principal barrier to BIM adoption is resistance stemming from individuals and organizations rooted in conventional practices. This result is similar with Olofsson Hallén et al. (2023), who describe how the most intangible aspects of an organization, particularly those related to the human subsystem, pose challenges in change. Despite the rapid advancements in information and communication technology (ICT) within the AEC sector over the last two decades, a pervasive resistance exists towards the change that these technologies offer (Zhao et al., 2018).

The findings indicate that this resistance to change is more noticeable among staff in public authorities compared to the private sector. Private companies appear to be actively striving to learn and adopt BIM for individual competitive advantages. This observation aligns with Wang et al. (2020), who explain that empirical evidence suggests organizational nature significantly influences behavioral resistance to BIM implementation, with design engineers from state-owned corporations exhibiting greater resistance compared to those from non-state-owned corporations (Wang et al., 2020). Additionally, current BIM guidelines are deemed insufficient in implementation, with the primary challenge lying in managing internal discussions regarding the appropriate approach. The predominant challenge arises from the entrenched mindset of individuals and companies accustomed to traditional modes of operation. The construction industry exhibits reluctance in embracing new technologies like BIM due to rooted habits and skepticism regarding its added value, with practitioners preferring to maintain the status quo. According to (Oesterreich & Teuteberg, 2019), resistance represents a common but intricate behaviour exhibited by individuals and groups when facing the uncertainty and perceived negative outcomes (such as a loss of the status quo) that accompany change. A preference for continuity, along with individual inertia and concerns about potential job or status loss, can lead to various forms of resistance to the implementation of new technologies (Oesterreich & Teuteberg, 2019). This finding is also supported by Zhao et al. (2018), who argue that people commonly resist change that threatens their perceived value, prioritizing their own best interests. The findings reveal that the challenge lies in shifting the industry's mindset from individual gain to collaborative improvement. Resistance to change is deeply entrenched in commercial interests, lack of incentives, and concerns about job security. Regarding this topic, Olofsson Hallén et al. (2023)'s study indicates that user acceptance of BIM technology may change over time as the organizational scope of acceptance evolves.

Lack of knowledge and Understanding

The results consistently indicate that a significant portion of clients lack a clear understanding when requesting BIM. It was observed that clients express a need for BIM without comprehending its meaning or how to utilize it effectively, demonstrating a lack of understanding of the overall process. Many clients exhibit a deficiency in understanding BIM's potential, failing to perceive its value beyond being a mere technical drawing tool. In alignment with this finding, Wang et al. (2020) explain that client support significantly influences the perceived usefulness of BIM, underscoring the distinct roles of management and client support in shaping perceptions related to BIM implementation (Wang et al., 2020). Supporting this finding, Olofsson Hallén et al. (2023) and Cao et al., (2022) argue that top-management support and guidance are crucial factors in fostering BIM acceptance within organizations. Users are more inclined to trust and accept innovations like BIM when they receive adequate guidance and when the technology is integrated into their familiar environment (Olofsson Hallén et al., 2023; Cao et al., 2022).

Adapting to BIM Evolutionary Race

The challenges associated with the rapid expansion of BIM were revealed through the interview findings, indicating the difficulty in allocating time for learning and embracing BIM, emphasizing that substantial training is essential to cultivate well-informed professionals in the field. For instance, one respondent noted that acquiring expertise in handling BIM took years, emphasizing the significance of accumulating further experience. Interview debates emphasize that beyond training and experience acquisition, cultural shifts are essential but require considerable time. Furthermore, the designers often encounter significant initial workload to generate drawings at the project's onset. Consequently, this results in the model becoming overly intricate and time-consuming, a factor not consistently considered by the client organization. The interview discussions underscore that clients may not always comprehend the expectations associated with BIM, and its utilization is rapidly evolving. It was elucidated that the rationale behind employing BIM is to mitigate risks and errors during project execution, necessitating planning for the requisite additional time and effort during the design phase while the designers working on creating the digital twin of the project in BIM environment.

Cultural Change

The findings illustrate that cultural evolution represents a significant struggle. Implementing changes within established practices proves challenging. It has been suggested that before implementing BIM, organizational culture must undergo transformation. The adoption of BIM necessitates a cultural shift, involving the sharing of risks and responsibilities among parties.

Some exhibit resistance due to a lack of familiarity. This result is supported by Zhao et al. (2018), who suggest that "inadequate relevant knowledge and expertise" contribute to "cultural resistance." BIM adoption, constituting an organizational change that reshapes design and construction processes, often encounters resistance due to personal attitudes shaped by perceived risks, implementation difficulties, and perceptions of others' opinions toward new technologies (Zhao et al., 2018). Cultural change is imperative for successful BIM adoption. Numerous project participants adhere to traditional work methodologies. According to the findings, this resistance to change is more pronounced among public organizations. Similarly, Borges Viana & Marques Carvalho (2021) argue that persistent cultural resistance is observed, particularly among public agencies' employees, who exhibit limited openness to altering established processes. There is reluctance to engage in relearning and overcome the inertia rooted in outdated technology (Borges Viana & Marques Carvalho, 2021).

Incentivizing systems

The interview results indicate that there is minimal motivation for designers to utilize BIM. The absence of contracts that adequately reimburse BIM work places a financial burden on design consultants. Suggestions have been made to implement strategies that encourage collaboration and establish a more rewarding system for BIM usage. Similarly, several other studies advocate for the redefinition of strategies, policies, and incentive systems to promote BIM acceptance (Howard et al., 2017; Okakpu et al., 2020).While some clients may voluntarily prefer BIM usage and be willing to pay extra for the effort, there is a lack of an overarching incentivizing and rewarding system for BIM utilization. For instance, one interviewee attributes the resistance to change to the prevailing hourly fee-based model, where clients are unwilling to pay additionally for using new technologies such as BIM. Although client arrangements are pivotal in introducing a rewarding approach, the recommended incentivizing system may not necessarily originate from the client. In the context of a Design-Build (DB) project, for instance, an interviewee from a contractor company mentions implementing a DB contract, rewarding the architect for following BIM Guidelines. The interviewee suggests that incentivizing stakeholders should be the approach to promote BIM adoption. Additionally, the interview results also proposed that BIM can facilitate the implementation of sustainable building practices and promote the reuse of materials during engineering, potentially motivating contracting companies undertaking Built Operate Transfer (BOT) projects. This approach may lead to improved profit margins.

Market Norm Evolution

The interview findings also suggest that while innovative approaches like BIM may offer a temporary advantage, competitors will catch up, and clients' expectations will increase. Furthermore, failure to meet these expectations could result in businesses being marginalized in the market and lose their reputation and social standing. This aspect is also explored in a study by Silverio et al. (2023), where it is noted that external pressure from various entities in the competitive environment significantly influences the organization's decision to adopt BIM. This notion is also supported by Smith (2014), who suggests that the drive for innovation to preserve competitiveness is a key motivator for BIM implementation (Smith, 2014).

BIM Training Gaps

According to the results, the limited adoption of BIM is attributed to companies' insufficient proficiency in BIM. Some organizations, especially government entities, continue to rely on two-dimensional documentation due to inadequate BIM training and skilled personnel. The importance of selecting experienced stakeholders and investing in training is emphasized to mitigate potential challenges in BIM implementation. Consistent with this finding, Ullah et al.

(2022) argue that BIM necessitates specialized learning and training for effective utilization. Training and learning are deemed essential for BIM-based processes such as building permit procedures. Conducting regular workshops, participating in BIM-related conferences, providing on-the-job or project-based training, integrating BIM training into company curricula, and engaging BIM specialists for staff training are all highlighted as significant activities for enhancing professional skills (Elijah & Oluwasuji, 2019).

Conclusion

In conclusion, the discussions in this research shed light on the significant social challenges and barriers hindering the widespread adoption and effective implementation of BIM in the construction industry. Resistance to change emerges as a prevalent barrier, rooted in organizational culture and individual attitudes. This resistance is compounded by a general lack of awareness and understanding about BIM's potential among clients, leading to unrealistic expectations and challenges in utilization. Furthermore, the absence of a proper reward system or incentive for using BIM poses a considerable obstacle. The reluctance to invest in training and the necessary cultural shift exacerbates these challenges. Government support and regulations play a vital role in providing training and promoting BIM adoption. Addressing these social challenges and barriers requires collaborative efforts from all stakeholders. Comprehensive BIM training programs, cultural transformation initiatives, and government assistance are essential components. By fostering a culture of collaboration, providing incentives for change, and standardizing processes through regulatory support, the industry can overcome these social challenges and pave the way for the widespread adoption of BIM.

References

Adamu, Z. A., Emmitt, S., & Soetanto, R. (2015). Social BIM: Co-Creation with Shared Situational Awareness. In *Journal of Information Technology in Construction* (ITcon) (Vol. 20). http://www.itcon.org/2015/16

Alreshidi, E., Mourshed, M., & Rezgui, Y. (2017). Factors for effective BIM governance. *Journal of Building Engineering*, 10, 89–101. https://doi.org/10.1016/j.jobe.2017.02.006

Blay, K. B., Tuuli, M. M., & France-Mensah, J. (2019). Managing change in BIM-Level 2 projects: benefits, challenges, and opportunities. *Built Environment Project and Asset Management*, 9(5), 581-596.

Borges Viana, V. L., & Marques Carvalho, M. T. (2021). Prioritization of risks related to BIM implementation in Brazilian public agencies using fuzzy logic. *Journal of Building Engineering*, 36. https://doi.org/10.1016/j.jobe.2020.102104

Cao, D., Shao, S., Huang, B., & Wang, G. (2022). Multidimensional behavioral responses to the implementation of BIM in construction projects: an empirical study in China. *Engineering, Construction and Architectural Management*, 29(2), 819–841. https://doi.org/10.1108/ECAM-09-2020-0735

Cao, D., Wang, G., Li, H., Skitmore, M., Huang, T., & Zhang, W. (2015). Practices and effectiveness of building information modelling in construction projects in China. *Automation in Construction*, 49(PA), 113–122. https://doi.org/10.1016/j.autcon.2014.10.014

Elijah, O. O., & Oluwasuji, D. J. (2019). An evaluation of training needs of the Nigerian construction professionals in adopting building information modelling. *Journal of Construction in Developing Countries*, 24(2), 63–81. https://doi.org/10.21315/jcdc2019.24.2.3

Faris, H., Gaterell, M., & Hutchinson, D. (2022). Investigating underlying factors of collaboration for construction projects in emerging economies using exploratory factor analysis. *International Journal of Construction Management*, 22(3), 514–526. https://doi.org/10.1080/15623599.2019.1635758

Flick, U. (2006). *An Introduction to Qualitative Research*. SAGE Publications Inc.

Gamil, Y., & Rahman, I. A. R. (2019). Awareness and challenges of building information modelling (BIM) implementation in the Yemen construction industry. *Journal of Engineering, Design and Technology*, 17(5), 1077–1084. https://doi.org/10.1108/JEDT-03-2019-0063

Howard, R., Restrepo, L., & Chang, C. Y. (2017). Addressing individual perceptions: An application of the unified theory of acceptance and use of technology to building information modelling. International *Journal of Project Management*, 35(2), 107–120. https://doi.org/10.1016/j.ijproman.2016.10.012

Merschbrock, C., Hosseini, M. R., Martek, I., Arashpour, M., & Mignone, G. (2018). Collaborative Role of Sociotechnical Components in BIM-Based Construction Networks in Two Hospitals. *Journal of Management in Engineering*, 34(4). https://doi.org/10.1061/(asce)me.1943-5479.0000605

Merschbrock, C., & Munkvold, B. E. (2015). Effective digital collaboration in the construction industry - A case study of BIM deployment in a hospital construction project. *Computers in Industry*, 73, 1–7. https://doi.org/10.1016/j.compind.2015.07.003

Mignone, G., Hosseini, M. R., Chileshe, N., & Arashpour, M. (2016). Enhancing collaboration in BIM-based construction networks through organisational discontinuity theory: a case study of the new Royal Adelaide Hospital. *Architectural Engineering and Design Management*, 12(5), 333–352. https://doi.org/10.1080/17452007.2016.1169987

Oesterreich, T. D., & Teuteberg, F. (2019). Behind the scenes: Understanding the socio-technical barriers to BIM adoption through the theoretical lens of information systems research. *Technological Forecasting and Social Change*, 146, 413–431. https://doi.org/10.1016/j.techfore.2019.01.003

Okakpu, A., Ghaffarian Hoseini, A., Tookey, J., Haar, J., & Ghaffarianhoseini, A. (2020). Exploring the environmental influence on BIM adoption for refurbishment project using structural equation modelling. *Architectural Engineering and Design Management*, 16(1), 41–57. https://doi.org/10.1080/17452007.2019.1617671

Olofsson Hallén, K., Forsman, M., & Eriksson, A. (2023). Interactions between Human, Technology and Organization in Building Information Modelling (BIM) - A scoping review of critical factors for the individual user. *In International Journal of Industrial Ergonomics*. 97. Elsevier B.V. https://doi.org/10.1016/j.ergon.2023.103480

Raja Mohd Noor, R. N. H., Che Ibrahim, C. K. I., & Belayutham, S. (2023). The nexus of key attributes influencing the social collaboration among BIM actors: a review of construction literature. *International Journal of Construction Management*, 23(6), 988–998. https://doi.org/10.1080/15623599.2021.1946902

Rogers, E. M. (1995). *Diffusion of Innovations* (4th ed., Vol. 12). New York.

Sackey, E., Tuuli, M., & Dainty, A. (2015). Sociotechnical Systems Approach to BIM Implementation in a Multidisciplinary Construction Context. *Journal of Management in Engineering*, 31(1). https://doi.org/10.1061/(asce)me.1943-5479.0000303

Silverio, A. K., Suresh, S., Renukappa, S., & Heesom, D. (2023). Status of BIM implementation in the Dominican Republic construction industry – an empirical study. *Journal of Engineering, Design and Technology*, 21(2), 417–441. https://doi.org/10.1108/JEDT-05-2021-0253

Smith, P. (2014). BIM implementation - Global strategies. *Procedia Engineering*, 85, 482–492. https://doi.org/10.1016/j.proeng.2014.10.575

Ullah, K., Witt, E., & Lill, I. (2022). The BIM-Based Building Permit Process: Factors Affecting Adoption. *Buildings*, 12(1). https://doi.org/10.3390/buildings12010045

Wang, G., Wang, P., Cao, D., & Luo, X. (2020). Predicting behavioural resistance to BIM implementation in construction projects: An empirical study integrating technology acceptance model and equity theory. *Journal of Civil Engineering and Management*, 26(7), 651–665. https://doi.org/10.3846/jcem.2020.12325

Zhao, X., Wu, P., & Wang, X. (2018). Risk paths in BIM adoption: empirical study of China. *Engineering, Construction and Architectural Management*, 25(9), 1170–1187. https://doi.org/10.1108/ECAM-08-2017-0169

A Review of Contract Management Maturity Models in the Construction Sector

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Abstract

Construction projects, being multidisciplinary, unique, long-lasting, and large-scale, emphasize the significance of contract management for successful project completion. Maturity models are highly valuable in evaluating the capabilities of companies in various areas, including contract management. While there are numerous studies on contract management maturity models (CMMM) in different sectors, there is a limited number of studies undertaken in the construction sector. This paper aims to provide a comparative analysis of the CMMMs in the construction sector. A total of 9 maturity models have been analyzed. According to the comparative analysis, existing CMMMs consist of various maturity levels and assessment criteria. While four of them consist of five levels, the rest have various levels. Maturity is measured through a questionnaire in most of the models, and the levels are based on industry best practices. Furthermore, the assessment criteria focus on various contract lifecycle phases, considering several aspects and competencies such as financial management, dispute resolution. Another noteworthy finding is that none of these models focus on subcontractor management. As a future study, a contract management maturity model will be developed for subcontractor management in the construction sector, offering applicable solutions for companies to achieve the highest level of contract management maturity.

Keywords: *construction sector, contract assessment, contract management maturity models, subcontractor management.*

Introduction

Contract management encompasses a structured process ensuring that all parties engaged in a contract thoroughly grasp their obligations and facilitate their fulfillment with maximum efficiency and effectiveness, thereby optimizing the value derived from the contract (Lowe, 2007). The increasing acknowledgment of contract management among stakeholders is attributed to factors such as globalization, the high volume of projects, and the complex nature of contracts (Gunduz & Elsherbeny, 2020). Companies that successfully manage contracts have confirmed that effective contract management largely depends on the processes used to create these contracts, hence companies need contract management maturity processes to sign and manage contracts successfully (Garrett & Rendon, 2015). A comprehensive review of scholarly literature and industry practices concerning maturity models in contract management has been conducted. As a result of this review, 9 maturity models were identified, of which only 3 were found to be specifically developed for contract management in the construction sector. This paper aims to present a comparative analysis of the existing contract management maturity models to delineate the various approaches, evaluation methods, and maturity levels used in the literature and practice. The results of this study will be utilized in the development of a contract maturity model for sub-contractor management in the next stage of the research.

Methods and Data Collection

The study was based on an extensive and structured literature review. The keywords 'Construction Sector', 'Contract Assessment', and 'Contract Management Maturity Models' and search engines ‘Google Scholar, ITU Tarıyorum, Taylor Francis, Science Direct, Research Gate, and Elsevier’ were used for the literature review. The review examined a total of 2 national and 12 international publications in the construction sector and 23 from other sectors. Additionally, industrial practices were also examined using the same key terms on general search engines. Technical reports prepared by various organizations and firms have also been analyzed to understand the current practices in the industry besides the academic literature. Identified contract management maturity models (CMMM) have been comparatively analysed in terms of the approaches, evaluation methods, and maturity levels used.

Review of the Contract Management Maturity Models

Companies need to have a high-performance standard to be successful in today's global business competition, and the maturity model provides a roadmap to identify and narrow gaps in resources and quality. The main purpose of maturity models is to establish a framework to improve business outcomes by assessing companies' strengths and weaknesses, thereby gauging the correlation between company performance and maturity level (Gomes et al., 2013). Maturity models are spread across various fields such as education, healthcare, energy, finance, construction, industry, and are used not only in project management but also in software, quality, procurement, business development, staff capacity, and product development (Jayanetti et al., 2022; Farrokh & Mansur, 2013). Some maturity models used in the construction sector, such as the Change Management Maturity Model, are often developed by expanding traditional maturity models and do not contain comprehensive and specific definitions for the construction sector (Jayanetti et al., 2022). Studies, conducted on contract management maturity models, have been summarized 9 maturity models, including 4 academic and 5 industrial practices, as outlined in Table-1 below. The reviewed contract maturity models are compared in terms of sector, maturity levels, maturity assessment method, focus/process points covered by the model, and contract lifecycle. The main contractor is selected to manage the project, including contract management, project financing, material and equipment procurement, and project progress monitoring in construction sector, and the performance of the main contractor is strongly linked to subcontractors. (Yoke-Lian et al., 2012). The reviewed models have not addressed subcontractor management issues.

Table 1. Comparison table of selected contract management maturity models.

Name of Model	Maturity Levels	Evaluation Method	Sector
Contract Management Process Assessment Model (CM-PAM)	Maturity levels have not been defined.	0- N/A 1- Never 2- Seldom 3- Sometimes 4- Mostly 5- Always	Other
Contract Management Maturity Model (CMMM)	Level-1: Ad-hoc Level-2: Basic Level-3: Structured Level-4: Integrated Level-5: Optimized	0- N/A, don't know 1- Never 2- Seldom 3- Sometimes 4- Usually 5- Always	Other
Contract Administration Performance Framework (CAPF)	Maturity levels have not been defined.	From 0 to 100	Construction
Assessment of Contract Management Capabilities	Maturity levels have not been defined.	5-point Likert scale	Construction
Contract Management Maturity Model	Level-1: Initial Level-2: Developing Level-3: Advanced Level-4: Optimised	A-Strongly disagree B-Disagree C-Agree D-Strongly Agree	Construction
Contract Lifecycle Management (CLM) Maturity Assessment Survey	Level-1: Ad-hoc Level-2: Basic Level-3: Structured Level-4: Integrated Level-5: Optimised	0- N/A, Unknown 1- Never 2- Seldom 3- Sometimes 4- Mostly 5- Always	Other
Contract Management – Self Assessment	Level-1: Aware Level-2: Reactive Level-3: Proactive Level-4: Managed Level-5: Optimised	There are answers for evaluating every levels.	Other
Contract Lifecycle Management (CLM) Maturity Assessment	Level-1: Ad-hoc Level-2: Basic Level-3: Formalized Level-4: Systematized Level-5: Innovative	There are answers for evaluating every levels.	Other
Contract Lifecycle Management (CLM) Maturity Assessment Tool	Level-1: Low Level-2: Medium Level-3: High	1-Strongly disagree 2-Disagree 3- Neutral 4-Agree 5-Strongly Agree	Other

Contract Management Process Assessment Model (CM-PAM)

The United Nations (UN) Joint Inspection Unit (JIU) has developed the Contract Management Process Assessment Model (CM-PAM) to assess its organizations' post-award phase contract management processes. The two main objectives of CM-PAM are: (i) to provide a structured assessment of activities during the contract management phase of its organizations, and (ii) following the publication of the report, to enable each organization to determine its level of development in these processes by receiving CM-PAM survey results and addressing strengths and weaknesses in the management of goods and services contracts. Although pre-execution phase is not examined in this model, a series of interconnected elements related to actions and decisions made before the signing of the contract are considered. The model comprises a total of 111 questions across 10 key categories, with 2 open-ended questions on the strongest and weakest aspects of contract management. Each question requires a score from 0 (unknown) to 5 (always) to be assigned. The 10 key categories are as follows: (1) Governance/enabling environment, (2) Risk management, (3) Performance monitoring, evaluating, and reporting, (4) Change management, (5) Financial, (6) Dispute management and resolution, (7) Contract close-out and lessons learned, (8) Information systems, (9) Human resources and capacity building, and (10) Assurance system and control. Maturity levels are not determined (Bartsiotas, 2014).

Contract Management Maturity Model (CMMM)

The Contract Management Maturity Model (CMMM) was developed by Rene Rendon in 2003, specifically for the United States Department of Defense (DOD), to evaluate the best practices associated with contract management maturity levels of relevant organizations throughout the 6 stages of the contract management process. This model defines an evolutionary roadmap for an organization's contract management process capability, from an immature process to a mature process. To enable an accurate and detailed assessment of process capability, the model is designed to reflect 6 contract management key process areas and the key practice activities in each process area separately for buyers and sellers. For buyers, key process areas include procurement planning, solicitation planning, solicitation, source selection, contract administration, and contract close out. For sellers, they involve presales activity, bid decision making, bid preparation, contract negotiation, contract administration, and contract close out. The model defines 5 maturity levels, namely (1) ad hoc, (2) basic, (3) structured, (4) integrated, and (5) optimized. It consists of a total of 62 questions, with 10 or 11 questions for each key process area. Respondents are asked to rate each question from 0 (unknown) to 5 (always). The model's questions assess contract management best practices, focusing on process strength, successful outcomes, management support, integration, and measurement (Rendon, 2009; Garrett & Rendon, 2015).

Contract Administration Performance Framework (CAPF)

Gunduz and Elsherbeny (2020) developed a Construction Contract Management Performance Framework (CAPF) using the modified Delphi method from the perspective of project management teams working in the construction sector for traditional types of contracts. CAPF is a global, systematic, functional, and multidimensional framework covering contract execution and contract closure phases, divided into three main components: support function, time line function, and core competency function. The support function also serves other components. 11 project management process groups have been identified at the sub-breakdown of functions. These process groups include project management and governance & start-up, team management, communication and relationship management, quality and acceptance management, performance monitoring and reporting management, document and record management, financial management, change and changes control management, claims and disputes resolution management, contract risk management, and close-out. This framework can address construction contract management issues and offer benefits to sector professionals. The framework consists of 93 contributory factors across 11 project management process groups. CAPF serves as both a qualitative and quantitative tool. It can guide teams in establishing all components of the construction contract management system or as an audit checklist. Additionally, it aids in continuous improvement and early detection of underperforming processes for necessary improvements. This study, developed in 2021, was applied to main contractors in two projects in Qatar the following year using fuzzy logic, and the processes were scored from 0 to 100. Maturity levels are not determined (Gunduz & Elsherbeny, 2020, 2021).

Assessment of Contract Management Capabilities

Park and Kim (2018) developed a contract management capability assessment to evaluate the contract management abilities of construction companies in Korea, identify vulnerable aspects of current contract management, and enhance their international competitive strengths. The assessment aimed to systematically derive some key elements that would be considered as an important measure. The assessment survey questions were focused on main contractors and specifically on construction contracts, excluding other contract types like design-build, turnkey, and EPC contracts. The survey aimed to identify core capabilities important to experts and assess capability gaps in contract management within Korean construction companies. The assessment had three stages: bid preparation, contract signing, and contract implementation and closing, with 18 main tasks and 47 capabilities. These were categorized into personal (professional skills) and organizational (resource management) aspects. Some tasks overlapped. This resulted in 42 personal and 17 organizational capabilities grouped into 5 personal and 2 organizational clusters. The survey used a 5-point Likert scale, but maturity levels were not assessed (Park & Kim, 2018).

Contract Management Maturity Model developed by Built Intelligence

The model developed by Built Intelligence is the only industrial contract management maturity model specifically developed for the construction sector among the models reviewed. This model focuses on six critical competencies that align with different stages of the contract lifecycle and includes a self-assessment survey consisting of 32 questions for these critical competencies, resulting in 4 maturity levels. Respondents are asked to choose one of 4 options, ranging from "strongly disagree" to "strongly agree," for each question. These critical competencies aim to optimize performance by integrating processes and technology. The relevant competencies are as follows: (1) people & culture, (2) planning & preparation, (3) design & engineering, (4) procurement, (5) project delivery & handover, (6) use, observe & respond’dur (Evans & Corr, n.d.).

Contract Lifecycle Management (CLM) Maturity Assessment Survey developed by Gatekeeper

The Contract Lifecycle Management Maturity Assessment Survey developed by the Gatekeeper platform is an assessment survey for contract lifecycle management maturity. This assessment survey consists of a total of 96 questions across 10 focus areas and includes 5 maturity levels. The 10 focus areas are as follows:(1) the governance environment, (2) risk management, (3) performance management, (4) change management, (5) financial management, (6) dispute management, (7) contract disengagement, (8) CLM staff capabilities, (9) technologies, (10) assurance systems. Each question represents an idealized scenario that would warrant the company's highest score if applicable. Respondents rate each question from 0 to 5. Scores below 4 need explanations; scores from 1 to 4 indicate potential issues. Maturity levels are calculated by comparing total scores to the maximum possible. The company's overall maturity is determined by summing scores across focus areas in the survey's summary tab (Gatekeeper, n.d.).

Contract Management-Self Assessment developed by Bearing Point

BearingPoint's Contract Management Maturity Level Model is designed to provide a quick and easy self-assessment for contract management based on numerous customer requests and the need for a comparative analysis. This model consists of a total of 10 self-assessment questions summarizing 258 questions that enable the initial assessment of contract management, along with 5 maturity levels. Unlike other models, appropriate answers have been prepared for each question based on maturity levels. The main topics of the questions include: (1) management attention and support, (2) contract management organisation, (3) contract management process, (4) support by IT tools (Point, 2015).

Contract Lifecycle Management (CLM) Maturity Assessment developed by WorldCC & Elevate

The model developed by World Commerce & Contracting and Elevate aims to define the readiness level of a company's contract lifecycle management for implementation. This assessment consists of 10 questions in total, with 5 main topics and 2 questions per topic, and includes 5 maturity levels. Similar to Bearing Point's self-assessment questionnaire, answers are prepared according to the maturity levels for each question. The relevant topics are as follows: (1) design/evaluation (contract request and contract depository), (2) assembly/approval (contract templates and clause library), (3) negotiation (contract playbook and contract triage), (4) implementation (contract approval and contract signature), and (5) performance (contract performance and obligation management). Following this assessment, next steps are determined according to the company's maturity level for development of the company's maturity, and the assessment results are shared (World Commerce and Contracting & Elevate, n.d.).

Contract Lifecycle Management (CLM) Maturity Assessment Tool developed by Info-Tech

The last one from industrial practices is a model developed by the Info-Tech Research Group. This model is specifically designed for the information technology sector. It examines the contract lifecycle in two phases: phase 1 consists of (1) request, (2) create, (3) review risk, (4) approve, (5) negotiate, and (6) sign stages; phase 2 consists of (7) capture, (8) manage, (9) compliance, and (10) optimize stages. The assessment tool comprises a total of 50 questions, with 5 questions for each stage, and includes 3 maturity levels. Questions are scored from 1 (strongly disagree) to 5 (strongly agree), with scores for each stage totalled and averaged for stage maturity. Overall maturity is calculated by averaging across all stages. Maturity levels range from low (1-2.4, needing attention) to average (2.5-3.75, with room for improvement) to high (above 3.75, showing ongoing improvement) (Info-Tech Research Group, n.d.).

Comparison of the Contract Management Maturity Models

The comparison reveals that (i) survey questions are prepared to represent the ideal scenario for companies' contract management maturity and the evaluation method is scoring in 7 models, while answers are prepared according to the relevant maturity level in 2 models; (ii) there is no maturity levels in 3 models, 2 models have maturity levels of 3 and 4 respectively, and 4 models have a maturity level of 5; (iii) maturity during contract execution and contract closure periods after contract signing is considered in 2 models, while the contract lifecycle is taken into account totally in the remaining models; (iv) only 3 models are specifically developed for the construction sector. Two of the models developed in the construction sector were encountered during an academic literature review, while one was created by a consultant company as an industrial practice. The CAPF, developed by Gunduz and Elsherbeny (2020), endeavours to provide a reliable tool that will increase awareness, visibility, monitoring, and control over contract management activities, enhance company efficiency and effectiveness, minimize contract-related issues, improve project control, and monitor personnel performance in successive stages leading to successful rewarding; on the other hand, Park and Kim (2018) have created an assessment study that can be used by large construction companies in Korea as well as individual firms, providing strategic guidance to strengthen contract management capabilities in construction projects abroad. These two models highlight best practices in contract management in the construction sector.

Conclusion and Future Works

Given the complexity of the construction sector, the critical role of contract management in successfully completing projects is paramount. The assessment of companies' contract management relies heavily on maturity models. While extensive research has been conducted on contract management maturity models in various sectors, there is relatively limited research in the construction industry. The significance of contract management in construction projects and the limited research highlight the necessity of developing and implementing maturity models for contract management in the construction sector. In this study, a comparative analysis of nine existing contract management maturity models was conducted. Among these models, only three of them are specific to the construction sector, while two of them are not developed as maturity models. This analysis revealed a significant gap in addressing subcontractor management within contract management maturity models in the construction sector. It is evident that there is a need for a specialized contract management maturity model focusing on subcontractor management by employers in the construction sector, and such a model is planned to be developed in future research. In this model, the contributory factors from the study developed by Gunduz and Elsherbeny (2020), personnel and organizational capabilities clusters from the study developed by Kim and Park (2018), key process areas from the model developed by Rendon (2009), and focus points from other relevant studies will be considered as main reference points. The development of this model will enable companies to effectively manage the complex challenges of construction projects, actively handle subcontractor contracts from the bidding phase to contract closure, enhance project delivery and stakeholder satisfaction, and evaluate personnel and organizational capacities separately.

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References

Bartsiotas, G. A. (2014). Contract management and administration in the United Nations system. *United Nations*, *9*(1), 1-85.

Evans, S. C., & Corr, C. (n.d.). *Contract Management Maturity Model*. https://info.builtintelligence.com/en-gb/download-contract-management-maturity-model-whitepaper

Farrokh, J., & Mansur, A. K. (2013). Project management maturity models and organizational project management maturity model (OPM3®): A critical morphological evaluation. *Project management*, *2*(7), 23-33.

Garrett, G. A., & Rendon, R. G. (2015). Improving The US Federal Acquisition Workforce, Part 2 of 3-Contract Management Process Maturity: The Key For Organizational Survival. *Contract Management*, *55*(6).

Gatekeeper (n.d.). *Contract Lifecycle Management (CLM) Maturity Assessment Survey*. https://www.gatekeeperhq.com/blog/how-to-assess-your-contract-management-capabilities

Gomes, J., Romão, M., & Caldeira, M. (2013). Linking benefits to maturity models. *Proceedings of the 15th International Conference of Academy of Management and Business (IAMB)*.

Gunduz, M., & Elsherbeny, H. A. (2020). Operational framework for managing construction-contract administration practitioners' perspective through modified Delphi method. *Journal of Construction Engineering and Management*, *146*(3), 04019110.

Gunduz, M., & Elsherbeny, H. A. (2021). Critical assessment of contract administration using multidimensional fuzzy logic approach. *Journal of Construction Engineering and Management*, *147*(2), 04020162.

Lowe, D. (2007). Contract management. *The Wiley Guide to Project Technology, Supply Chain & Procurement Management*, 317.

Info-Tech Research Group (n.d.). *Contract Lifecycle Management (CLM) Maturity Assessment Tool.*https://www.infotech.com/research/ss/assess-your-it-financial-management-maturity-effectively

Jayanetti, J. K. D. D. T., Perera, B. A. K. S., & Waidyasekara, K. G. A. S. (2022). *Defining a 'maturity model' in the construction context: A systematic review.*

Park, S. H., & Kim, Y. S. (2018). An assessment of contract management capabilities for overseas construction projects. *KSCE journal of civil engineering*, *22*, 2147-2158.

Rendon, R. G. (2010). *Contract management process maturity: Empirical analysis of organizational assessments*. Acquisition Research Program.

Point, B. (2015). *Contract Management 2010–How Excellent Contract Management Can Improve Your Business Success*. 2010. Saatavissa: https://www.bearingpoint.com/files/0553_WP_EN_Vertragsmgt_final_web.pdf[viitattu 25.01. 2013].

Yoke-Lian, L., Hassim, S., Muniandy, R., & Teik-Hua, L. (2012). Review of subcontracting practice in construction industry. *International Journal of Engineering and Technology*, *4*(4), 442.

World Commerce and Contracting, & Elevate (n.d.). *Contract Lifecycle Management (CLM) Maturity Assessment Tool.* https://elevate.worldcc.com/a/def/5d93322bec3345.10388116/start

Construction-Related Disputes: A Comprehensive Bibliometric Investigation

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Abstract

Construction disputes are figuratively a hump on the back of the construction industry. Due to the loss of quality, time, and cost, the issue of construction disputes has been the subject of increasing research intensity in recent years. In this study, the related studies conducted from 1970 to the end of 2023 were analyzed in detail to reveal the topics, keywords, and trends, on which the studies frequently focused on. The annual publication growth rate, the distribution of studies, and the authors according to the countries were presented with different analyses, dealing with 2,475 engineering-specific studies. It was found that the average annual publication rate is 11.60%, while the average number of citations per file is 11.76%. Moreover, it was observed that there has been a significant increase in this research area since 2016 and the USA, China, and the UK have prioritized the studies. In the case of the last three years specifically, topics such as smart contracts, deep learning, and blockchain have been trending in the field of construction dispute research. The observed increasing trend indicates the significance of dispute resolution not only in developing countries but also in developed countries.

Keywords: *bibliometric analysis, construction disputes, project management.*

Introduction

The construction industry has a complex and difficult project management process. Since the technical, legal, and administrative knowledge levels of the parties are not equal and their priorities are different, various disputes may occur throughout the project processes (Sari et al., 2021). It is also known that disputes cause material and moral losses to all parties in the project process. There have been ongoing studies for many years to minimise or completely prevent these losses. This study presents a quantitative scientific basis that will be put forward on issues, such as which issues the ongoing studies are related to, what the trends are, which countries and which researchers are followed intensively (Olalekan et al., 2021). In the light of the findings revealed by the bibliometric analysis method, the researchers' command of the topic will increase. Researchers will easily identify gaps in the literature via this approach, which reveals study trends and frequencies from a broader perspective.

Literature Review

Construction disputes are a research topic that directly or indirectly affects construction project management. Prior studies were started by investigating the causes of claims and disputes in construction project management (Kumaraswamy, 1997; Molenaar et al., 2000; Semple et al., 1994), and the effects of stakeholders on project success (Chan et al., 2004; Cheng et al., 2000; Olander, 2007). In the following years, the field has increased its impact by linking studies with building information modeling-BIM (Zhang & Hu, 2011), natural language processing-NLP (Zhang & El-Gohary, 2013), deep learning (Akinosho et al., 2020) and blockchain (Tao et al., 2023).

Garcia et al. (2022) identified the applications of the machine learning method in the construction industry and the areas with potential for its use. Focusing on studies between 2015 and 2022, the researchers used the hybrid bibliometric method. In the field of construction law, Khademi Adel et al. (2022) revealed the current studies and trends in the legal field of civil engineering. They created the dataset using different keywords from the Web of Science (WoS) database for 20 years period (2000-2019). They performed several approaches similar to bibliometric analysis, using the scientometric analysis method.

Previous studies indicate that the bibliometric method is frequently used to reveal the relationships between dynamic research topics in detail. With the increasing application of artificial intelligence-based studies, the research topics in this field have diversified. Lu and Zhang (2022) proposed policies to increase productivity by analyzing heterogeneous big data in the construction industry. They evaluated 1,253 articles from between 1992 and 2020 years through general statistical analysis, keyword co-occurrence analysis, and bibliometric analysis.

The conducted studies utilized the bibliometric method indicate that specific studies have been conducted with specific keywords (Khademi Adel et al., 2022; Olaolu Titus Olalekan et al., 2021; Wu et al., 2023). To summarize, the requirement for a more comprehensive study that will fill the research gap and evaluate the literature from a broad perspective has emerged. This study aims to contribute to the knowledge of construction disputes.

Method

The general methodology of this study is the bibliometric analysis. Bibliometric analysis is the analysis of scientific studies and data such as publications or citations by quantitative methods (Fairthorne, 1969; Pritchard, 1969). The main purpose of using the bibliometric analysis rather than the cumbersomeness of classical methods, in cases where the number of data is very high and the scope of the investigation is wide, is to reveal the current status of the research topic and the trends in this subject (Donthu et al., 2021). Applications related to bibliometric analysis can be observed in different fields; for example, economy (Bonilla et al., 2015), supply chain management (Fahimnia et al., 2015), health (Ahmad & Slots, 2021), etc. The methodology flowchart of the stages of bibliometric analysis are presented in Figure 1 and detailed below.

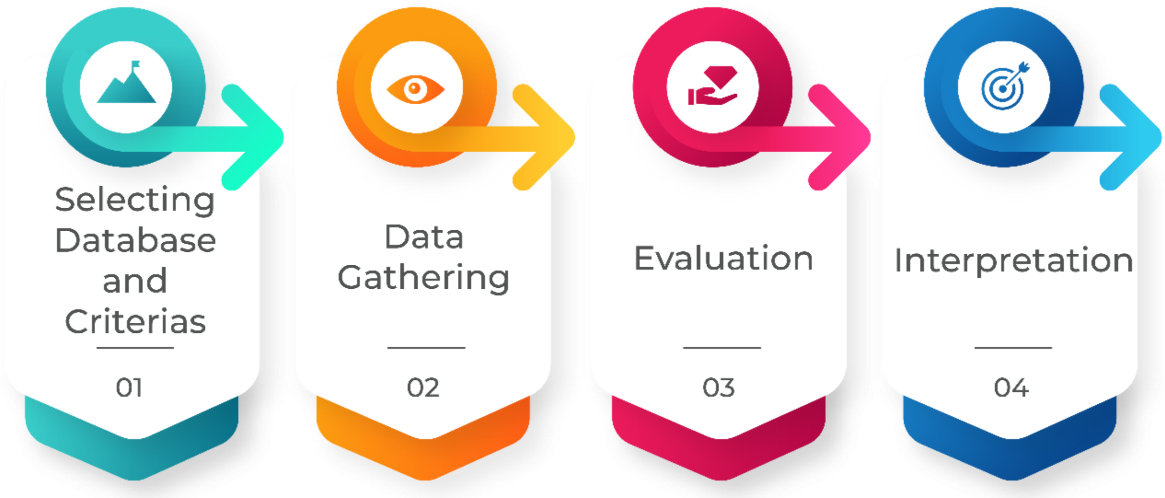

Figure 1: Flowchart of the methodology.

- **Selecting Database and Criteria:** Databases such as WoS, Scopus, and Google Scholar are frequently used to collect data for research studies. In this study, the more inclusive Scopus database (Mongeon & Paul-Hus, 2016; Singh et al., 2021) was preferred. Scientific studies in the Scopus database between 1970 and 2024 were focused on. For data collection, "construction AND industry" OR "building project" AND "dispute" OR "conflict" were used as the search criteria. The study was limited to studies in the field of "engineering" and English written. All criteria were searched in the keywords, title, and abstract of the data.

- **Data Gathering:** In the light of the determined criteria, a total of 5,798 scientific studies were collected from the Scopus database between 1970 and 2024 years. For the sub-analysis of the method to function properly, the year 2024 was not included since the academic publication process in 2024 has not been completed. As a result, 2,544 scientific studies between 1970 and 2023 were analyzed in this study. All studies were reviewed in terms of content and found to be related to the search criteria. As a result of the analyses, 69 studies that were not related to the search criteria and duplication were removed from the dataset. The number of datasets remaining after data filtering is 2,475.

- **Evaluation:** The data obtained were integrated into the R Studio program for the bibliometric analysis. 'Bibliometrix library' and 'Shinny interface' were used to perform the analyses. These analyses can be classified as performance analysis, science mapping, and network analysis.

- **Interpretation:** Tables, graphs, and relationship maps were used to interpret the analyses. Publication-related, citation-related, citation-and-publication-related metrics, citation, co-citation, co-word and co-authorship analyses, and interpretations were performed.

Results and Discussion

The obtained data was initially analyzed via performance analysis, which is one of the main techniques of the bibliometric analysis as aforementioned. The metrics indicated that there are 2,475 documents from 750 different sources between 1970 and 2023 years. 52% of these documents are 1,276 articles, 37% are 905 conference proceedings and 11% are other types of academic publications. It can be interpreted that the number of publications has increased in recent years and the publications -only- in the last seven years constitute 43% of the total publications, as presented in Table 1.

Table 1. Distribution of documents between 1970 and 2023 by year.

No	Year Range	Number of Documents	Percentage (%)
1	1970-1990	118	4,77%
2	1991-2000	226	9,13%
3	2001-2005	218	8,81%
4	2006-2010	425	17,17%
5	2011-2015	429	17,33%
6	2016-2019	414	16,73%
7	2020-2022	645	26,06%
Total		**2,475**	**100%**

It was observed from the database that there were 4,606 authors in total, 667 were single-author (14%) and there were 2.52 co-authors per document. While the average annual publication production rate was 10.27%, the average number of citations per publication was 13.47. Moreover, 13.82% of the co-authorship is at the international level. In terms of recent years, 127 publications in the 2021 year, reached 178 publications with a significant increase (40%) in 2023 year (Figure 2).

It was observed that the 10 most influential publications received an average of 278,2 citations in total and an average of 18.03 citations per year, as seen in Table 2. In terms of country variable, the USA (1,052) was found as the top country followed by China (411) and the United Kingdom (372). The leading institutions on the other hand are; (i) City University of Hong Kong with 64 publications, (ii) University of Johannesburg with 28 publications, (iii) Universiti Teknologi Malaysia, and (iv) University of Wolverhampton with 25 publications.

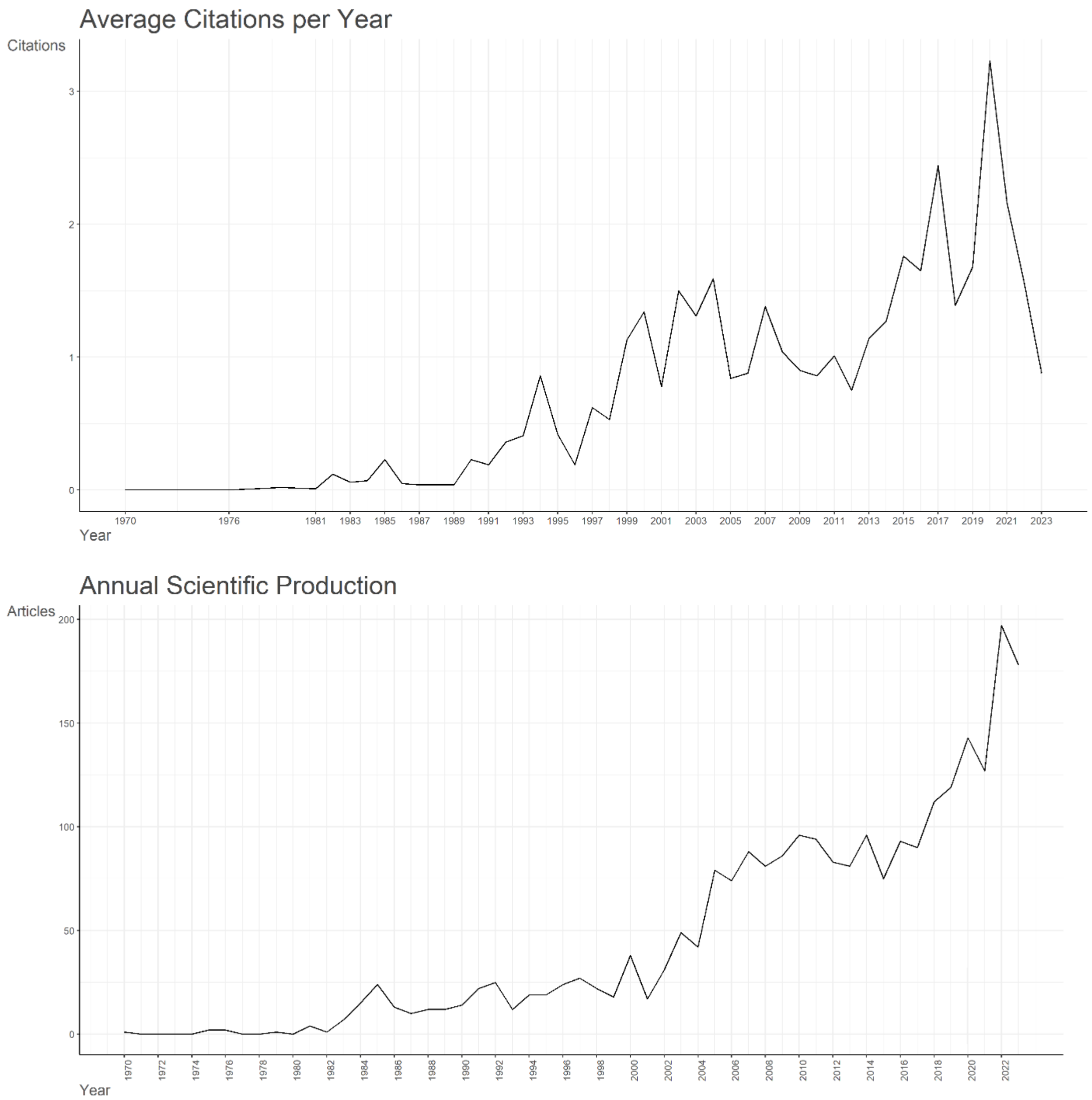

Figure 2: a) Average number of publications per year, b) Number of citations per document.

Table 2. Details of the 10 most influential publications.

No	Paper	Total Citations	TC per Year
1	Koo B, 2000, Journal of Construction Engineering and Management	382	15.28
2	Chan Apc, 2004, Journal of Construction Engineering and Management	336	16.00
3	Olander S, 2007, Construction Management and Economics	306	17.00
4	Wang Z, 2020, Automation in Construction	297	18.36
5	Akintoye A, 2003, Construction Management and Economics	266	12.09
6	Chen L, 2014, Automation in Construction	264	24.00
7	Borrego M, 2013, Journal of Engineering Education	238	19.83
8	Zhang J, 2016, Journal of Computing in Civil Engineering	234	26.00
9	Dossick Cs, 2010, Journal of Construction Engineering and Management	231	15.40
10	Hu Z, 2011, Automation in Construction	228	16.29
	Average	**278.2**	**18.03**

Considering the number of publications (SCP), in which the corresponding author and co-authors are from the same country; the USA was found as the top (208/2475, 8%). China was the top (37/2475, 2%) in the number of publications (MCP) co-authored by authors from different countries. From the perspective of Balkan countries, Türkiye, which is the only Balkan country in the top 20, ranks 11th with a value of 21/2 (SCP/MCP) (Figure 3). Considering the ranking of the most cited countries, the USA with 4,258 citations was followed by China with 3,188 citations, and Hong Kong with 2,469 citations.

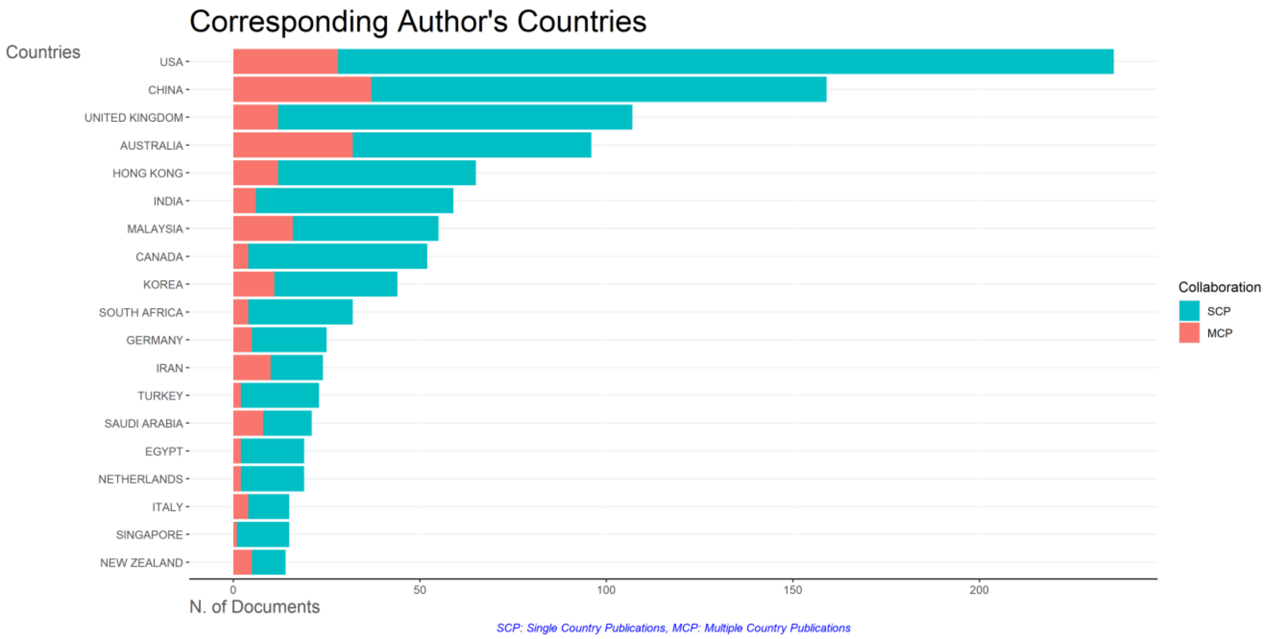

Figure 3: Top 20 countries ranking in terms of SCP and MCP

Word clouds are one of the pioneering applications in science mapping, which is one of the basic techniques of bibliometric analysis. Looking at the word cloud consisting of the first 50 words frequently mentioned in the keywords identified by 4,606 authors, it was determined that the terms dispute resolution (f=112), construction management (f=96), project management (f=70), claims (f=64), BIM (f=58), contracts (f=49), arbitration (f=41), collaboration (f=35) and building information modeling (f=31) were highlighted (Figure 4). While creating the word cloud, keywords used in the search were not included.

Figure 4: Word cloud scheme.

Looking at the trending topics in the four years (2016-2019) before the COVID-19 pandemic, it was seen that collaboration (f=34), case study (f=18), and construction contracts/contract (f=36) are trending along with the main topics. However, it was observed that the trends have changed significantly after the COVID-19 pandemic (Figure 5a). Looking at the trending topics in the four years (2020-2023) after the COVID-19 pandemic, it is noteworthy that BIM/Building Information Modelling (f=117), blockchain (f=17), and smart contracts (f=13) are the new trends (Figure 5b).

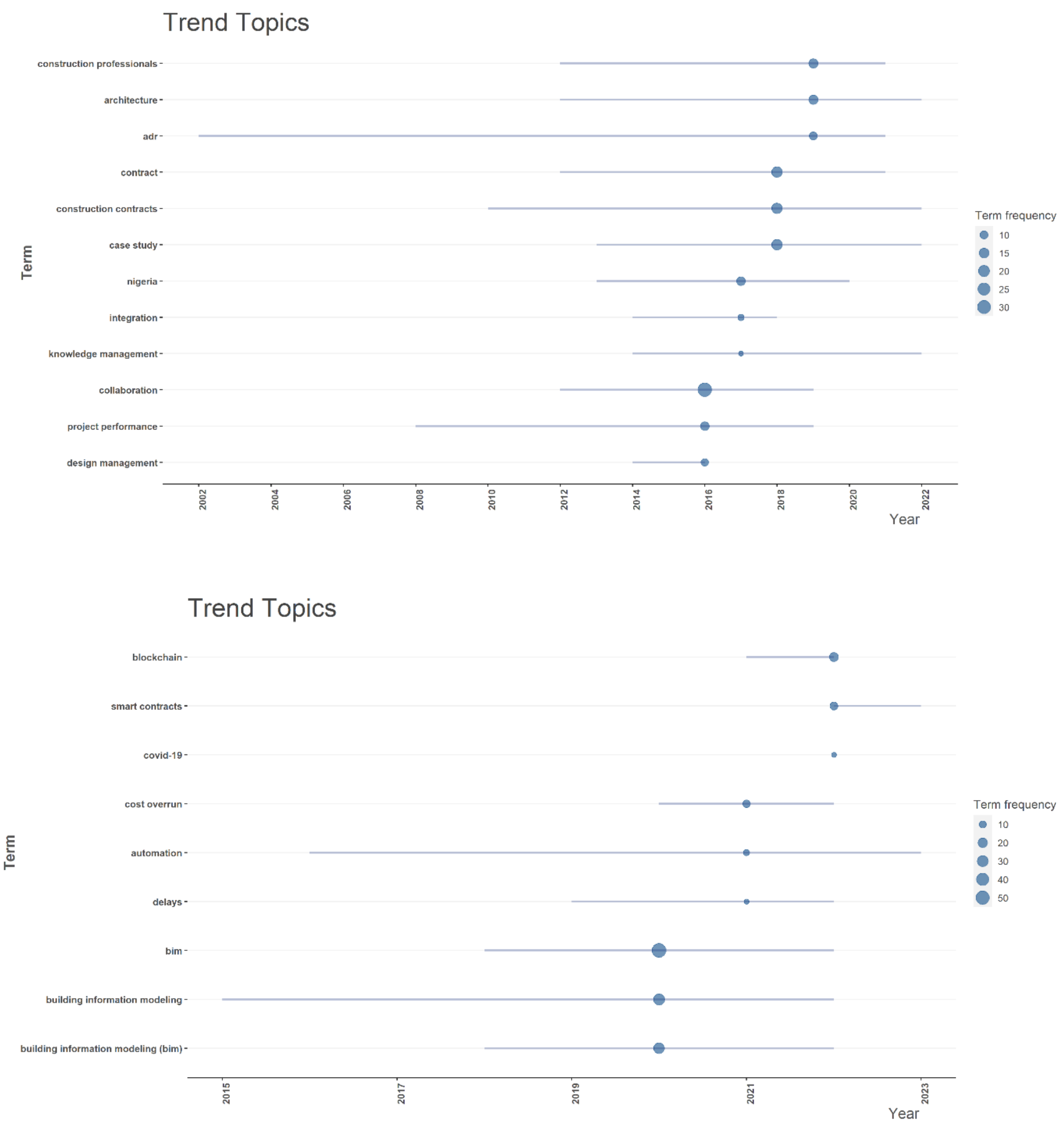

Figure 5a and b: Trending topics before the COVID-19 Pandemic (2016-2019) and trending topics after the COVID-19 Pandemic (2020-2023).

Looking at the thematic evolution of the studies from the perspective of the last quarter of the 20th century and the first quarter of the 21st century, it was seen that in the last quarter and the first five years of the new century, procurement, adjudication, work-family conflict, construction contracts, collaboration and alternative dispute resolution (ADR) have received more attention. When we look at the new century according to three different intervals before the COVID-19 pandemic, the interest of researchers has shifted towards more detailed topics. In the first interval (2006-2010), specialized topics such as game theory, partnering, sustainability, innovation, and conflict management came to the fore. In the second interval (2011-2016), in addition to the topics in the first interval, specialized topics such as sustainable development, CAD, risk assessment, decision-making, and building information modeling (BIM) come to the fore. In the third interval (2017-2019), the period before the COVID-19 pandemic, artificial intelligence comes to the fore, unlike BIM, ADR, and risk assessment, which were prominent in the second interval. When we look at the post-COVID-19 pandemic period (2020-2023), while BIM, ADR, and sustainability topics remain current, Blockchain stands out. Figure 6 shows the evolution of the themes according to years.

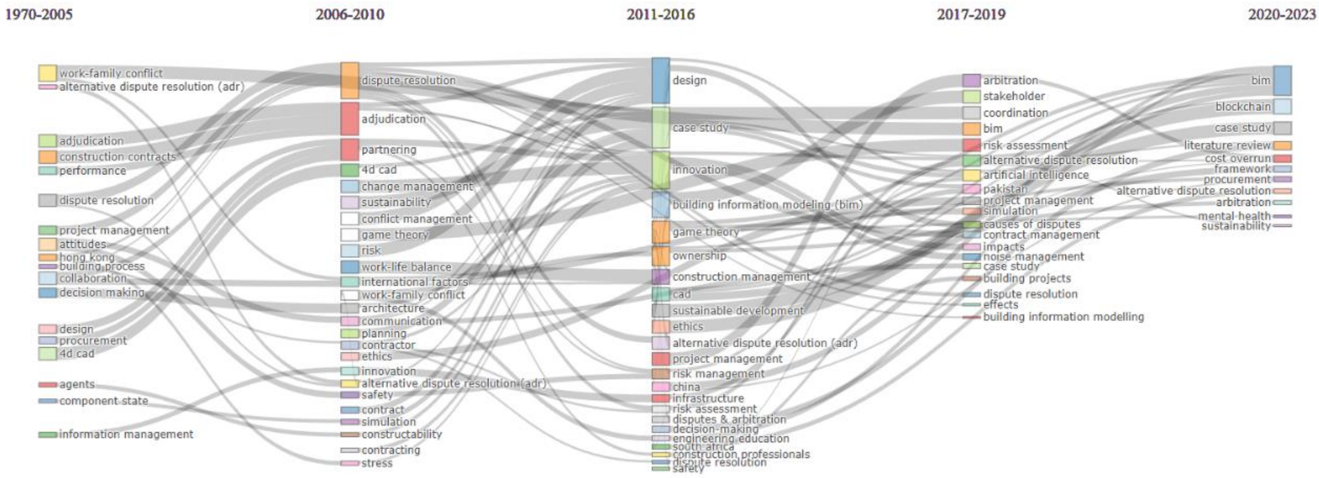

Figure 6: Evolution of themes over the years.

The co-occurrence network analysis showed that seven different groups emerged. The dominant group (in green colors) contains themes related to dispute resolution and construction management. This group includes keywords such as delay, scheduling, risk management, performance, and factor analysis. In the second group (in purple colors), related themes under the title BIM exist. This group includes themes such as design and planning. The third group (in orange colors) can be evaluated under the title of arbitration. Red, brown, and pink colored small groups can be expressed as productivity, safety, and case study (Figure 7).

Figure 7: Co-occurence network.

Conclusion

The data of 2,475 academic studies centered on disputes in the construction industry with certain keywords between 1970 and 2023 years were subjected to quantitative analysis using the Scopus database. To provide a broad perspective to the researchers working on the research with this study, 2,475 studies that are not repetitive and related to the search criteria of the academic studies that emerged as a result of the search were centered. In this respect, the study overlaps with some studies (Olaolu Titus Olalekan et al., 2021). On the other hand, the current study differs from some studies that focus only on article type in their studies (Garcia et al., 2022; Khademi Adel et al., 2022; Lu & Zhang, 2022; Wu et al., 2023). In addition, the fact that 52% of the academic publications used in the study were articles, 37% were conference proceedings and 11% were other academic publications is important in terms of determining the future and trends of studies in the field.

The thematic evolution of the topics determined in this study over the years is remarkable. The academic adventure, which started with topics that were more general in the first years of the study, has evolved into more specific and innovative topics in recent years. Some studies overlap with the outputs of the thematic evolution of the study on research topics (Garcia et al., 2022). When we evaluate the impact of the COVID-19 pandemic on trending topics, it is seen that collaboration, construction contracts, and case study studies were trending before the pandemic. However, after the pandemic; blockchain, smart contracts, and BIM topics are more specific and parallel to the social and economic effects of the pandemic. The fact that trend topics have tended to different topics such as blockchain and smart contracts in recent years is in line with the study of Khademi Adel et al. (2022). Looking at the trends in the field of construction law, it can be emphasized that artificial intelligence has been trending since 2010 (Khademi Adel et al., 2022). However, the fact that the current study was able to identify a more specific (blockchain) topic as a trend can be interpreted as high effectiveness.

In terms of the co-occurrence network analysis, more detailed and clearer group distinctions and group members are identified. With these results, the current study is in parallel with some studies (Garcia et al., 2022; Lu & Zhang, 2022; Wu et al., 2023), while some studies show that these groups do not go beyond general headings and our study differs (Khademi Adel et al., 2022; O. T. Olalekan, Ariffin, Ali, Raslim, & Mohamad, 2021).

The researchers can access trending issues and trends in disputes in the construction industry based on the aforementioned findings. Moreover, the potential of which countries and organizations can be collaborated with can be measured. By observing the developing technological trends, it will be easier for researchers to orientate towards future topics. The fact that this study was performed only with academic studies obtained from a database limits the study. More effective and efficient academic studies can be conducted by selecting keywords that are more specific, many databases, and specific types of academic publications on trending topics.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Ahmad, P., & Slots, J. (2021). A bibliometric analysis of periodontology. *Periodontology 2000, 85*(1), 237-240.

Akinosho, T. D., Oyedele, L. O., Bilal, M., Ajayi, A. O., Delgado, M. D., Akinade, O. O., & Ahmed, A. A. (2020). Deep learning in the construction industry: A review of present status and future innovations. *Journal of Building Engineering, 32*, 101827. https://doi.org/https://doi.org/10.1016/j.jobe.2020.101827

Bonilla, C. A., Merigó, J. M., & Torres-Abad, C. (2015). Economics in Latin America: A bibliometric analysis. *Scientometrics, 105*(2), 1239-1252. https://doi.org/10.1007/s11192-015-1747-7

Chan, A. P. C., Chan, D. W. M., Chiang, Y. H., Tang, B. S., Chan, E. H. W., & Ho, K. S. K. (2004). Exploring critical success factors for partnering in construction projects. *Journal of Construction Engineering and Management, 130*(2), 188-198. https://doi.org/doi:10.1061/(ASCE)0733-9364(2004)130:2(188)

Cheng, E. W. L., Li, H., & Love, P. E. D. (2000). Establishment of critical success factors for construction partnering. *Journal of Management in Engineering, 16*(2), 84-92. https://doi.org/doi:10.1061/(ASCE)0742-597X(2000)16:2(84)

Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., & Lim, W. M. (2021). How to conduct a bibliometric analysis: An overview and guidelines. *Journal of Business Research, 133*, 285-296. https://doi.org/https://doi.org/10.1016/j.jbusres.2021.04.070

Fahimnia, B., Sarkis, J., & Davarzani, H. (2015). Green supply chain management: A review and bibliometric analysis. *International Journal of Production Economics, 162*, 101-114. https://doi.org/https://doi.org/10.1016/j.ijpe.2015.01.003

Fairthorne, R. A. (1969). Empirical hyperbolic distributions (Bradford-Zipf-Mandelbrot) for bibliometric description and prediction. *Journal of Documentation, 25*(4), 319-343. https://doi.org/10.1108/eb026481

Garcia, J., Villavicencio, G., Altimiras, F., Crawford, B., Soto, R., Minatogawa, V., Franco, M., Martínez-Muñoz, D., & Yepes, V. (2022). Machine learning techniques applied to construction: A hybrid bibliometric analysis of advances and future directions. *Automation in Construction, 142*. https://doi.org/https://doi.org/10.1016/j.autcon.2022.104532

Khademi Adel, T., Modir, M., & Ravanshadnia, M. (2022). An analytical review of construction law research. *Engineering, Construction and Architectural Management, 29*(5), 1931-1945. https://doi.org/10.1108/ECAM-05-2020-0306

Kumaraswamy, M. M. (1997). Conflicts, claims and disputes in construction. *Engineering, Construction and Architectural Management, 4*(2), 95-111. https://doi.org/10.1108/eb021042

Lu, Y., & Zhang, J. (2022). Bibliometric analysis and critical review of the research on big data in the construction industry. *Engineering, Construction and Architectural Management, 29*(9), 3574-3592. https://doi.org/10.1108/ECAM-01-2021-0005

Molenaar, K., Washington, S., & Diekmann, J. (2000). Structural equation model of construction contract dispute potential. *Journal of Construction Engineering and Management, 126*(4), 268-277. https://doi.org/doi:10.1061/(ASCE)0733-9364(2000)126:4(268)

Mongeon, P., & Paul-Hus, A. (2016). The journal coverage of Web of Science and Scopus: A comparative analysis. *Scientometrics, 106*, 213-228.

Olalekan, O. T., Ariffin, H. L. B. T., Ali, K. N., Raslim, F. M., & Mohamad, M. B. (2021). Bibliometric analysis of construction dispute. *Malaysian Construction Research Journal, Specialissue12*(1), 64-75. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85107634489&partnerID=40&md5=6bafa1e451ae17c3bd08ff5ccf0a3cd7

Olander, S. (2007). Stakeholder impact analysis in construction project management. *Construction Management and Economics, 25*(3), 277-287. https://doi.org/10.1080/01446190600879125

Pritchard, A. (1969). Statistical bibliography or bibliometrics. *Journal of Documentation, 25*, 348.

Sari, M., Sayin, B., & Akcay, C. (2021). Classification and resolution procedure for disputes in public construction projects. *Revista de la Construcción. Journal of Construction, 20*(2), 259-276. https://doi.org/https://doi.org/10.7764/RDLC.20.2.259

Semple, C., Hartman, F. T., & Jergeas, G. (1994). Construction claims and disputes: Causes and cost/time overruns. *Journal of Construction Engineering and Management, 120*(4), 785-795. https://doi.org/doi:10.1061/(ASCE)0733-9364(1994)120:4(785)

Singh, V. K., Singh, P., Karmakar, M., Leta, J., & Mayr, P. (2021). The journal coverage of Web of Science, Scopus and Dimensions: A comparative analysis. *Scientometrics, 126*, 5113-5142.

Tao, X., Wong, P. K.-Y., Xu, Y., Liu, Y., Gong, X., Zheng, C., Das, M., & Cheng, J. C. P. (2023). Smart contract swarm and multi-branch structure for secure and efficient BIM versioning in blockchain-aided common data environment. *Computers in Industry, 149*, 103922. https://doi.org/https://doi.org/10.1016/j.compind.2023.103922

Wu, G., Zhu, Y., & Hu, Z. (2023). A bibliometric review of research on interorganizational conflicts in the construction industry: 1989-2021. *International Journal of Conflict Management, 34*(1), 181-212. https://doi.org/10.1108/IJCMA-03-2022-0051

Zhang, J., & El-Gohary, N. M. (2013). Semantic NLP-based information extraction from construction regulatory documents for automated compliance checking. *Journal of Computing in Civil Engineering, 30*(2), 04015014. https://doi.org/doi:10.1061/(ASCE)CP.1943-5487.0000346

Zhang, J. P., & Hu, Z. Z. (2011). BIM- and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction: 1. Principles and methodologies. *Automation in Construction, 20*(2), 155-166. https://doi.org/https://doi.org/10.1016/j.autcon.2010.09.013

The Impact of Diversification Strategy on Economic Growth: Evidence from the Construction Industry

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Abstract

Diversification, in the context of economic development, is a multifaceted concept that has long been associated with the pursuit of sustainable economic growth. This study aims to examine the relationship between diversification and economic growth from the perspective of the construction industry. Moreover, through a comprehensive review of existing literature and empirical evidence, this study seeks to provide insights into the role of diversification in fostering competitive advantage in the construction industry. Consequently, it was revealed that a diversification strategy has a key role in achieving sustainable economic growth through the opportunities created. This strategy contributes to economic resilience and prosperity through the effect of risk spreading or reducing, innovation, and enhancing competitiveness. Therefore, diversification can be considered a notable strategy for the construction industry and sustainable economic growth.

Keywords: *construction industry, diversification, growth, strategy.*

Introduction

Diversification, the process of expanding economic activities across multiple sectors, industries, or markets, has been a central focus of economic policy and research for decades. The motivation behind diversification can be reducing dependence on a single industry or sector and promoting economic growth by enhancing resilience, innovation, and competitiveness or reducing risks (Ye et al., 2018). Economic growth has been a significant issue for developing countries (Fischer, 1987) and growth can be prolonged by diversifying businesses (Viner, 1932). The growth in the construction industry has been characterized as one of the key factors of the expansion of economic growth in the national economy (Preece et al., 2011). Therefore, the success or failure of the construction industry was seen as a significant indicator of the robustness and growth of the national economy (Zopounidis & Paraschou 2013). For example, a total of 10% improvement in the construction industry could contribute to the economic growth of the US and thus may stabilize Social Security in the US through this contribution (Ibrahim et al., 2020). Therefore, survival and growth strategies for the construction industry should be taken into account to maintain sustainable development in both developed and developing economies (Wong et al., 2010).

The construction industry has been characterized by poor performance for decades and is quite familiar with economic cycles or recessions similar to the economic growth patterns that experience cyclical fluctuations (Ruddock et al., 2014). The competitive environment of the construction industry forces firms to make strategic choices to improve their long-term performance (Azman et al., 2020). Since the construction industry reveals a more complex and competitive business environment, firms diversify their activities through several markets or industries to survive and stay competitive. For example, large construction firms tend to diversify to implicate a corporate strategy to survive or provide economic growth (Kim & Reinschmidt, 2011a). However, extending business activities to other industries or markets may increase the risks to emerging competitors and business environments (Jang et al., 2019). Therefore, construction firms should employ this strategy carefully to respond to changing economic and environmental factors (Han et al., 2019). In this regard, this study reveals the impact of a diversification strategy on economic growth from the perspective of the construction industry.

The Growth of Construction Firms

The volume of the construction market may reach $15.5 trillion worldwide by 2030 and according to Figure 1, three countries (i.e., China, the US, and India) will be leading countries accounting for 57% of all global growth (Global Construction 2030, 2015).

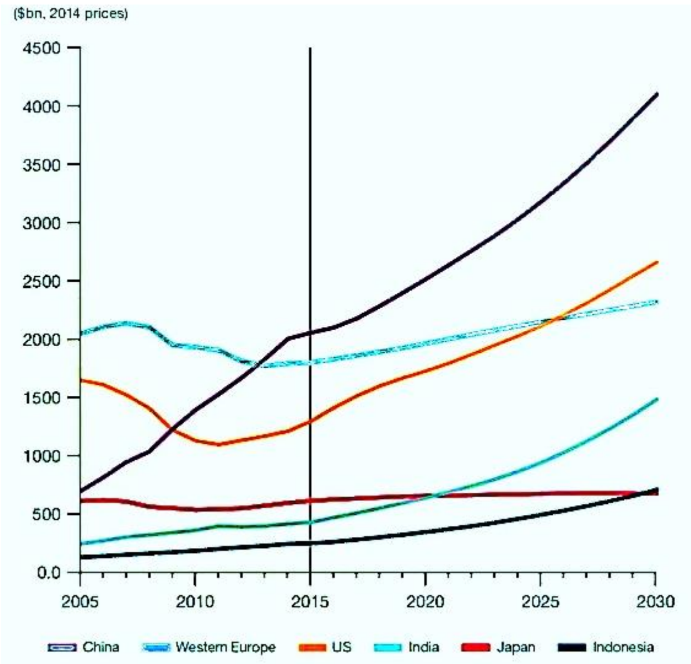

Figure 1: Growth of the global construction market (Global Construction 2030, 2015).

Construction firms pursue profitable growth in this business environment to maintain a balance between the exploitation of existing capabilities and the exploration of new possibilities (Raisch, 2008). It is a fact that the growth of construction firms may result in a positive contribution to the development of the national economy of a country (Abu et al., 2011). The international construction market has been growing significantly around developing economies (Han et al., 2010) and large construction firms choose diversification as a corporate strategy for growth. The characteristics of the construction industry force construction firms' growth to be achieved by a revenue increase from the present market and by new revenue from diversification (Kim & Reinschmidt, 2011a). To monitor the growth performance of construction firms the growth rate of sales or the growth rate of the asset scale can be utilized (Sung et al., 2017). Consequently, achieving sustainable growth in the construction industry may depend on the successful implementation of a diversification strategy.

The Diversification of Construction Firms

Diversification is a corporate strategy for growth and risk management (Kim & Reinschmidt, 2011b). This strategy can foster innovation through the exchange of knowledge and technologies across industries. For instance, investments in research and development in one sector can lead to technological spillovers that benefit other sectors. Moreover, it was accepted as a survival strategy to the main business in a competitive environment. The diversification strategy of construction firms determines the portfolio of different businesses in various sectors (Kim & Reinschmidt, 2011a). They prefer this strategy more in the low growth and recession periods of the economy than periods of high growth (Sung et al., 2017). During recession periods, firms seek mergers with or acquisitions of other businesses (28%), to explore overseas business opportunities (27%) and to expand in the growth business areas (24%) (Ruddock et al., 2014). From the perspective of the construction industry, diversification enables firms to show better growth performance, provide regular cash flow, reduce or spread business risks, maintain market dominance, and provide supply chain advantages through backward integration.

Figure 2 presents the overall diversification behavior of the 400 US contractors using the diversity index measure. A low firm diversity index connotes specialization or focus and lower market diversification, high diversity index (close to one) indicates the opposite. Hence, over 15 years, about 35% of the US contractors were focused or specialized, and about 65% applied diversification.

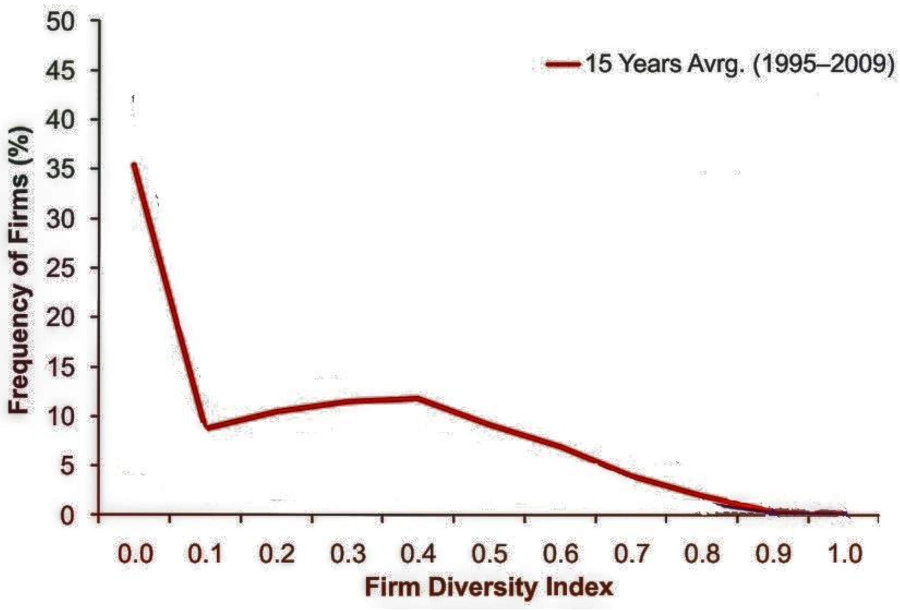

Figure 2: Overall pattern of market diversification (Kim and Reinschmidt, 2011b).

Economic Growth and Diversification

Economic growth is a fundamental goal for nations worldwide. It signifies the overall improvement in living standards, job creation, and the ability to invest in essential public services. Recklies (2001) states that growth has to be part of corporate development and firms can benefit from the effects of growth such as economies of scale, increased profits, power, and prestige (Weinzimmer, 2000). However, overreliance on a single industry or economic sector can be precarious. Bonaccorsi and Giannangeli (2008) noted that growth may bring a cost for firms while enabling the profitability of new market opportunities.

Construction firms should improve or develop their business strategy to achieve growth regarding three key steps (Figure 3). First of all a deep understanding of the fundamental concepts of profitability through the industry should be developed. Secondly, operational excellence and commercial effectiveness should be provided to seek new investment opportunities by concentrating on organizational and financial capabilities. Lastly, construction firms must chase innovation and new technologies to gain competitive advantages over existing or emerging competitors (Diplock et al., 2019).

To ensure long-term economic stability and prosperity, diversification may act as an economic shock absorber by mitigating the impact of sector-specific economic downturns. A business strategy that is heavily reliant on a single industry, could become quite vulnerable to external shocks. Therefore, diversification can be regarded as one of the vital strategies to make an economy less susceptible to fluctuations in one sector.

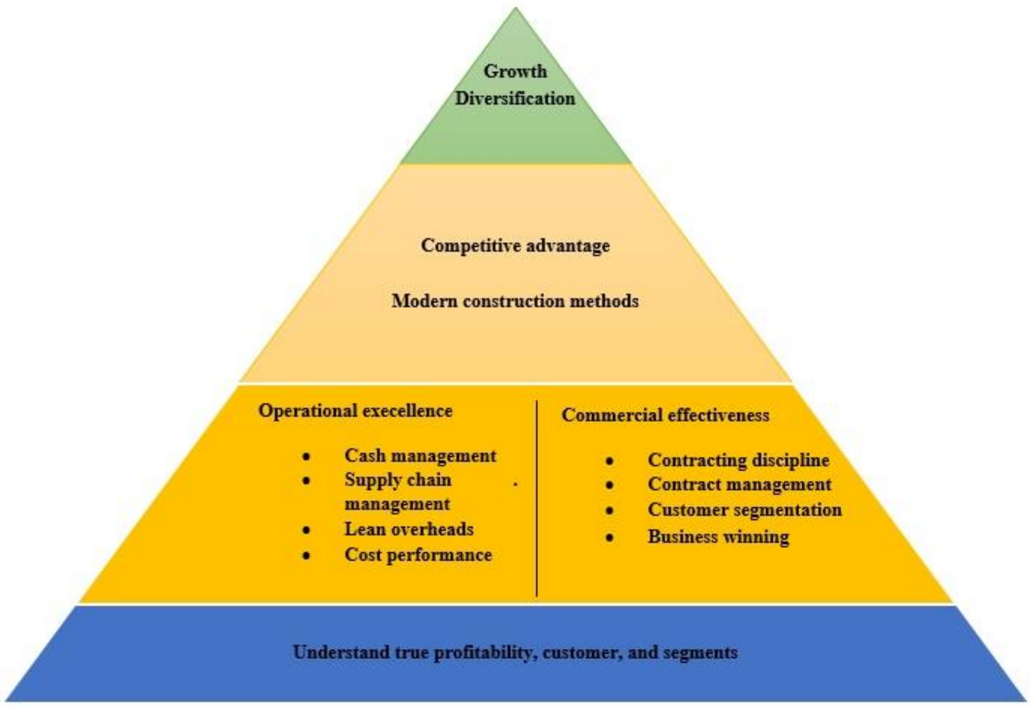

Figure 3: Steps to competitive advantage (Diplock et al., 2019).

The construction industry presents fragile, competitive, and risky industry characteristics. Therefore, the growth strategies of construction firms should be considered significant to survive in such a business environment. Firm growth demands flexibility to utilize emerging technologies, improve labor skills and organization of production process, and serve in different markets (Abu et al., 2011). In this regard, diversification can be considered one of the most effective business strategies to maintain economic growth for construction firms.

Good management execution was expressed as a vital criterion to contribute to the growth of a construction firm. The most important factors for a successful growth performance for construction firms were listed as good firm management; good cash flow management; sufficient knowledge and experience; good team members; technical expertise; good site management; commitment to customer satisfaction; availability of capital; availability of skilled workers; and good relations with clients (Abu et al., 2011). These factors can enable the firm to win more projects, increase annual revenue, and achieve growth (Jewell et al., 2014). The growth strategy can be linked to entering new markets in the construction industry and operating in related/unrelated markets (Ozdogan & Birgonul, 2001). The growth performance of a construction firm can be measured through firm size, turnover (sales volume), profits, number of employees, and share prices (Hillebrandt & Cannon, 1989; Choi & Russell, 2005). There is a correlation between the increase in sales volume and diversification of building and infrastructure firms, and they tend to diversify during the period of recessions (Sung et al., 2017). In addition, diversified firms have higher growth rates than undiversified ones (Kim & Reinschmidt, 2012).

Nowadays, growth is a significant and challenging issue for any firm (Raisch, 2008). As contractors may create new opportunities to maintain growth by exploring new markets and industries, completing international projects also becomes important for sustainable growth (Han et al., 2010). Construction firms should execute a well-designed diversification strategy to sustain their growth path, spread risks through entering new markets, and take advantage of the opportunities offered by the global economy (Olivier & Root, 2014). Similarly, exploring all new markets/industries is a necessity for construction firms to sustain the growth performance of the construction industry (Ofori & Chan, 2000). Construction firms also prefer diversification to provide a good growth performance (Jewell et al., 2014).

Conclusions and Recommendations

Diversification should be regarded as a key strategy for achieving sustainable economic growth. This strategy has a great opportunity to contribute to economic resilience and prosperity through the effect of risk spreading or reducing, seeking innovation, and enhancing competitiveness. Empirical evidence and past studies consistently support the idea that diversification is associated with positive economic outcomes, making it a subject of enduring interest and importance in the field of economics. The growth achieved in the construction industry has a great potential to provide economic growth in the national economy of a country. Therefore, to benefit from the advantages of diversification, good top management, and solid strategic management should be organized in firms.

Future studies can be performed to evaluate the effect of diversification strategy on growth by analyzing financial data of the construction industry and economic development statistics in a specific country. Another future research can be conducted examining the effect of the business performance of diversified construction firms over secondary industries.

References

Abu, H. A. B., Arman, A. R., Mohamad, N. Y., & Nurkhuraishah, A. K. (2011). Factors determining growth of companies: a study on construction companies in Malaysia. *African Journal of Business Management*, *5*(22), 8753-8762.

Azman, M. A., Hon, C. K. H., Xia, B., Lee, B. L., & Skitmore, M. (2020). Product diversification and large construction firm productivity: the effect of institutional environments in Malaysia. *Engineering, Construction and Architectural Management 28*(4), 994-1013.

Bonaccorsi, A., & Giannangeli, S. (2008). One or more growth process? Evidence from new Italian firms. *Small Business Economics*, *35*, 137-152.

Choi, J., & Russell, J. S. (2005). Long-term entropy and profitability change of United States public construction firms. *Journal of Management in Engineering*, *21*(1), 17-26.

Diplock, T., Wheatland, J., & Singh, H. (2019). Back to basics: why the U.K. construction sector must focus on fundamentals. *L.E.K Insights*, *21*(1).

Fischer, S. (1987). Economic growth and economic policy. In V. Corbo, M. Goldstein, & M. Khan (Eds.), *Growth-oriented adjustment programs*. IMF-World Bank.

Global Construction 2030. (2015). Global construction market to grow $8 trillion by 2030: driven by China, US, and India. https://www.vindobona.org/article/global-construction-market-to-grow-8-trillion-by-2030-driven-by-china-us-and-india

Han, M., Lee, S., & Kim, J. (2019). Effectiveness of diversification strategies for ensuring financial sustainability of construction companies in the Republic of Korea. *Sustainability (Switzerland)*, *11*(11), 3076-3095.

Han, S. H., Kim, D. Y., Jang, H. S., & Choi, S. (2010). Strategies for contractors to sustain growth in the global construction market. *Habitat International*, *34*(1), 1-10.

Hillebrandt, P. M., & Cannon, J. (1990). *The modern construction firm*. Macmillan.

Ibrahim, M. W., Hanna, A. S., Russell, J. S., Abotaleb, I. S., & El-Adaway, I. H. (2020). Comprehensive analysis of factors associated with out-of-sequence construction. *Journal of Management in Engineering*, *36*(4), 1-9.

Jang, Y., Ahn, Y., Park, M., Lee, H. S., & Kwon, N. (2019). Business models and performance of international construction companies. *Sustainability (Switzerland)*, *11*(9), 1-16.

Jewell, C., Flanagan, R., & Lu, W. (2014). The dilemma of scope and scale for construction professional service firms. *Construction Management and Economics*, *32*(5), 473-486.

Kim, H. J., & Reinschmidt, K. F. (2011a). Diversification by the largest US contractors. *Canadian Journal of Civil Engineering*, *38*(7), 800-810.

Kim, H., & Reinschmidt, K. F. (2011b). Association of risk attitude with market diversification in the construction business. *Journal of Management in Engineering*, *27*(April), 66-74.

Kim, H., & Reinschmidt, K. F. (2012). Market structure and organizational performance of construction organizations. *Journal of Management in Engineering*, *28*(2), 212-220.

Ofori, G., & Chan, S. L. (2000). Growth paths of construction enterprises in Singapore, 1980-98. *Engineering, Construction and Architectural Management*, *7*(3), 307-321.

Olivier, J., & Root, D. (2014). The diversification strategies of large South African contractors into southern Africa. *Journal of the South African Institution of Civil Engineering*, *56*(2), 88-96.

Ozdogan, I. D., & Birgonul, M. T. (2001). Diversification strategies of Turkish construction companies. *Proceedings of CIB World Building Congress*, New Zealand.

Preece, C. N., Low, S. P., Padfield, R., & Papargyropoulou, E. (2011). Developing and marketing sustainable construction services. *Proceedings of International Conference on Management and Innovation for a Sustainable Built Environment*, Netherlands.

Raisch, S. (2008). Balanced structures: designing organizations for profitable growth. *Long Range Planning*, *41*(5), 483-508.

Recklies, O. (2001). *Managing growth – barriers and preconditions*. http://themanager.org/pdf/ManagingGrowthII.PDF.

Ruddock, L., Kheir, A., & Ruddock, S. (2014). UK construction companies' strategies in the face of business cycles. *International Journal of Strategic Property Management*, *18*(3), 225-237.

Sung, Y. K., Lee, J., Yi, J. S., & Son, J. (2017). Establishment of growth strategies for international construction firms by exploring diversification-related determinants and their effects. *Journal of Management in Engineering*, *33*(5).

Viner, J. (1932). Cost curves and supply curves. *Journal of Economics*, *3*(1), 23-46.

Weinzimmer, L. G. (2000). A replication and extension of organizational growth determinants. *Journal of Business Research*, *48*, 35-41.

Wong, J. M. W., Thomas N. S, & Chan, A. P. C (2010). Strategic planning for the sustainable development of the construction industry in Hong Kong. *Habitat International*, *34*(2), 256-263.

Ye, M., Lu, W., Flanagan, R., & Ye, K. (2018). Diversification in the international construction business. *Construction Management and Economics*, *36*(6), 348-361.

Zopounidis, C., & Paraschou, D. (2013). *Multicriteria decision aid methods for the prediction of business failure*. Springer.

Unlocking the Potential of Business Intelligence in the Construction Industry

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Abstract

Business Intelligence (BI) is a new strategy and technology that converts organizational data into meaningful and actionable information for managers. The business intelligence process is based on transforming data into information, information into decisions, and ultimately, decisions into actions. In the construction industry, various business intelligence tools are needed to analyze various aspects of construction projects, evaluate encountered opportunities and challenges, provide benefits in areas such as time, cost, risk management, etc., and enhance the success rate and return on investment of construction projects, and analyze long-term plans and decisions. Despite the many possible benefits of business intelligence in the construction industry, its use is limited. This paper employs bibliometric analysis to provide evidence from the literature regarding the limited use of business intelligence in the construction industry. This study aims to raise awareness of business intelligence in the construction industry and thus increase its use in the future.

Keywords: *bibliometric analysis, business intelligence, construction industry, project management.*

Introduction

Business intelligence is a broad term that includes structures, applications, databases, tools, and processes for organizing and analysing data into relevant and useful information to improve managerial decision-making (Nithya & Kiruthika, 2022). A business intelligence system transforms an organization's data into knowledge by consolidating it, then allows organizations to quickly and easily review large amounts of information, and gives the organization the ability to process that information intelligently (Lago & Cantero, 2013). Business intelligence is an accessible method that improves the quality of the decision-making process (Oliveira et al., 2021). It aims to support the decision-making process by meeting the information needs of decision-makers (Vuori, 2007; Furmankiewicz et al., 2015). Organizational employees can access corporate data instantly using business intelligence techniques, enabling them to make faster and more accurate decisions (Mavi & Standing, 2018).

There are many business intelligence tools with different applications in the construction industry (Lopes & Boscarioli, 2020). Golestanizadeh et al. (2023) state that project managers require business intelligence tools to analyse different aspects of construction projects, evaluate opportunities and challenges, increase success rates and returns and analyse long-term plans and decisions due to the growing volume of construction projects. The application of business intelligence and analytical tools improves the performance of the management and decision-making process in the construction industry (Lopes & Boscarioli, 2021). By making the right decisions, construction project managers not only increase project performance but also make organizations more agile and gain competitive advantage over other organizations by discovering and identifying management opportunities (Petrini & Pozzebon, 2009).

Lack of skills and knowledge of technological tools in the construction industry and organizational culture leads to less commitment to technologies. This makes it difficult for the construction industry to adopt technologies (Majrouhi Sardroud, 2015; Viljamaa & Peltomaa, 2014; Lu et al., 2014). It can be stated that the necessity of innovation in the construction industry plays an important role in the development of the economy and the future of the country (Mandicak et al., 2016). The adoption of digital technologies leads the construction industry to the low-risk industry and helps to reduce many risks in construction projects (Davila Delgado et al., 2019). Business intelligence, one of the digital technologies, reduces risks with its strategic support function and is seen as the assurance of the decision-making process (Vuori, 2007).

According to Golestanizadeh et al. (2023), despite the importance of business intelligence, very few studies have investigated the use of business intelligence in construction projects. Organizations in the construction industry and other industries have a significant gap towards new technologies for improving management principles. Therefore, an analysis of the potential benefits for organizations related to the implementation of technologies that improve the performance of management processes and influence their expansion in the market should be conducted (Lopes et al., 2020).

Research Methodology

This study reviews the literature to raise awareness about the limited use of business intelligence in the construction industry by adopting a systematic literature review. To achieve this, the use of business intelligence in the construction industry was analysed through, a bibliometric analysis.

Bibliometric analysis, as a systematic quantitative literature review, follows a transparent, detailed and repeatable review process to collect and systematize information (Pollack & Adler, 2015). Moreover, it is goal-oriented due to its quantitative nature and involves statistical analysis of bibliometric data (Grant & Booth, 2009). For a given research topic, bibliometric analysis helps to understand the underlying concept, reflects the existing knowledge base and determines the direction of future research (Mok et al., 2015). This approach is usually based on the analysis of "co-authorship", "co-occurrence", "citation", "bibliographic linkage" and "co-citation" (Van Eck & Waltman, 2012).

Version 1.6.20 of VOSviewer software was used to perform bibliometric analysis within the scope of this study. The software provided statistical mapping based on bibliometric information on the use of business intelligence in the construction industry. To investigate the use of business intelligence in the construction industry, a literature review was conducted in the Scopus database, using the following search string.

TITLE-ABS-KEY (("BUSINESS INTELLIGENCE" OR "BUSINESS ANALYTICS") AND ("CONSTRUCTION SECTOR" OR "CONSTRUCTION INDUSTRY" OR "CONSTRUCTION MANAGEMENT" OR "CONSTRUCTION PLANNING" OR "CONSTRUCTION ENTERPRISE" OR "CONSTRUCTION WORK" OR "BUILDING CONSTRUCTION"))

The search string was created to align with the scope and objective of the study. A detailed explanation for the elements of the search string is provided in Table 1. The string was used in a comprehensive search query of the Scopus database, and the resulting data was obtained.

Table 1. The elements of the search string.

Keyword	Inclusion criteria
Business Intelligence	Focus on the central theme of business intelligence.
Business Analytics	Focus on statistical and quantitative analysis methods to support business decisions by analysing business data
Construction Sector/ Construction Industry	Focus on the construction, development, and maintenance of buildings and infrastructure, and all economic activities related to designing, constructing, and maintaining structures.
Construction Management	Focus on an interdisciplinary field involving the planning, organization and supervision of construction projects
Construction Planning	Focus on the process of a construction project that determines the timeline, budget, resources and other key factors
Construction Enterprise	Focus on an organization that executes, organizes and manages construction projects
Construction Work	Focus on the physical construction, material procurement, labour coordination and other related processes of a construction project
Building Construction	Focus on the process of designing, constructing and completing a building

The search was conducted on January 10, 2024, and 37 publications were obtained. The results comprise 18 journal papers, 16 conference papers, 2 book series, and 1 book chapter. The publications were not filtered by year of publication, language of writing, source of publication etc., due to the small number of results. The titles and abstracts of the publications were screened for high relevance to the scope of the thesis. The primary factor at this stage is the implementation of business intelligence in the construction industry.

The database was narrowed down to 25 publications related to business intelligence, which were then exported for use in VOSviewer software.

Results and Discussion

This section presents the results obtained from the bibliometric analysis.

Trend of Publications and Leading Journals in the Field

Figure 1 shows the annual trend of the 25 publications resulting from research on the use of business intelligence in the construction industry. Over the 16-year period from 2007 to 2023, there is no linear increase or decrease in the numerical distribution of publications within this research area. The graph shows that 48% of the publications were published between 2018 and 2023. However, it cannot be concluded that the use of business intelligence in the construction industry sector has been increasing in recent years. Despite this, given the rapid increase in digitalization, it is inevitable that business intelligence will become more prevalent in the construction industry, which has traditionally been distant from technology.

Furthermore, the research yielded 25 publications, each published in a different journal or conference. This indicates that there is no single prominent journal in the research area.

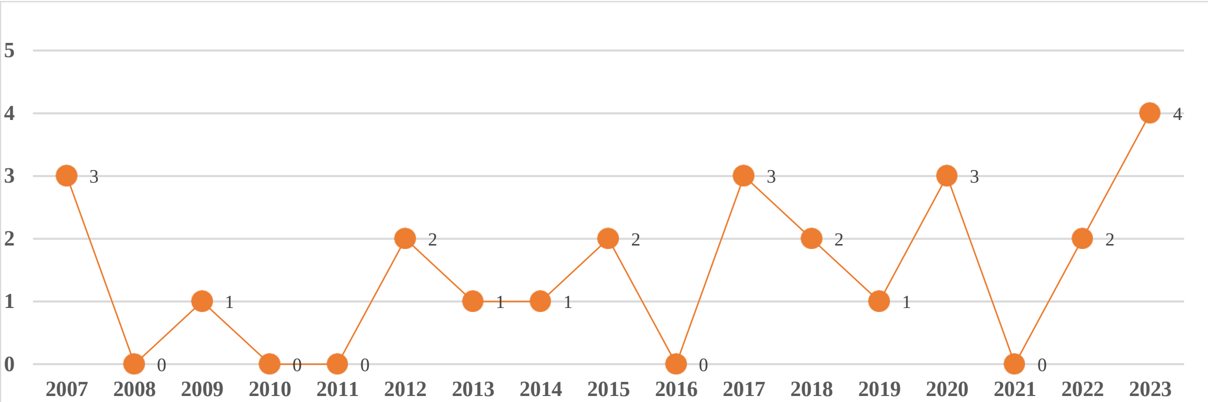

Figure 1: Yearly publication trend.

Citation Analysis: Identification of Prominent Papers

The influence of academic materials in a research field can be determined by the number of citations they receive (Ranjbari et al., 2021). Therefore, citation analysis was conducted using VOSviewer software as part of this thesis. Table 2 displays the ten most cited papers among the 25 relevant publications on the use of business intelligence in the construction industry. The journal paper' Business Performance Analytics: exploring the potential for Performance Management Systems', published in 2018, has received the most citations with a total of 51. Following this paper, there is a notable decrease in the number of citations for other publications.

Table 2. The top ten papers with the highest citations in the field.

Title	Total Citations	Author(s)	Publishing Journals
Business Performance Analytics: exploring the potential for Performance Management Systems	51	Raffony et al. (2018)	Production Planning and Control
Intelligent Facility Management for Sustainability and Risk Management	9	Kučera & Pitner (2013)	IFIP Advances in Information and

			Communication Technology
Digital quality management in construction	8	Marsden (2019)	Digital quality management in construction
4D and 5D BIM: A system for automation of planning and integrated cost management	7	Çelik (2020)	Communications in Computer and Information Science
Business Intelligence for Construction Company Acknowledgement Reporting System	5	Girsang et al. (2018)	1st INAPR 2018 - Proceedings
Construction Management Supported by BIM and a Business Intelligence Tool	5	Rodrigues et al. (2022)	Energies
A practical framework for assessing business intelligence competencies of enterprise systems Using fuzzy ANP approach	5	Rouhani & Ravasan (2015)	International Journal of Applied Decision Sciences
Business intelligence activities in construction companies in Finland- A series of case studies	4	Vuori (2007)	Proceedings of ECKM
Intelligent decision support system for construction project monitoring	3	Riaz & Husain (2012)	INMIC 2012
Web-based integrated project controls system	1	Montaser & Montaser (2017)	ISARC 2017

Identification of Prominent Countries and Institutions

In order to identify the countries and institutions that contribute to the use of business intelligence in the construction industry, an analysis was conducted using VOSviewer software. Figure 2 displays the number of publications produced by different countries, with the size of the circles representing this quantity. The lines in the figure indicate the connections between the publications.

The analysis of 25 documents showed that they were published in 19 different countries. China had the highest number of publications (3) on the use of business intelligence in the construction industry, representing 12% of the total number of publications. Iran, the United Kingdom, Malaysia, the United States, Egypt, Portugal, Turkey, and Indonesia contributed two documents each. The remaining countries (shown in Figure 2) published only one document each.

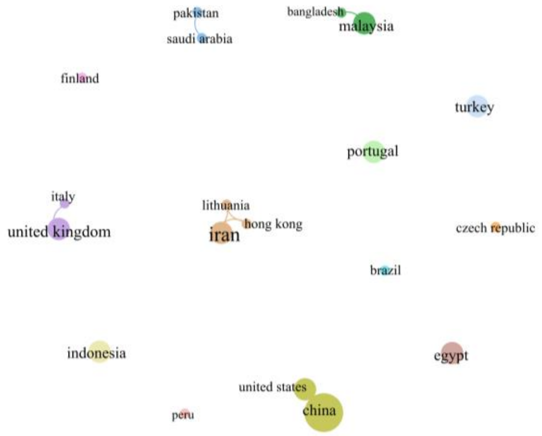

Figure 2: Illustration of collaboration nexuses of countries.

The analysis indicates that the majority of publications are not interconnected. According to Figure 2, Hong Kong, Lithuania and Iran have the highest number of links, with two links each. Lithuania and Hong Kong produced one publication each, while Iran produced two. Figure 3 provides a graphical representation of the number of publications and connections between countries.

In addition, the most cited publications, with 51 citations, belong to Italy and the United States, which produced the only documents on the subject, as revealed in previous analyses. The United States is the most cited country, with 59 citations. China, which has the highest number of publications, only has one citation.

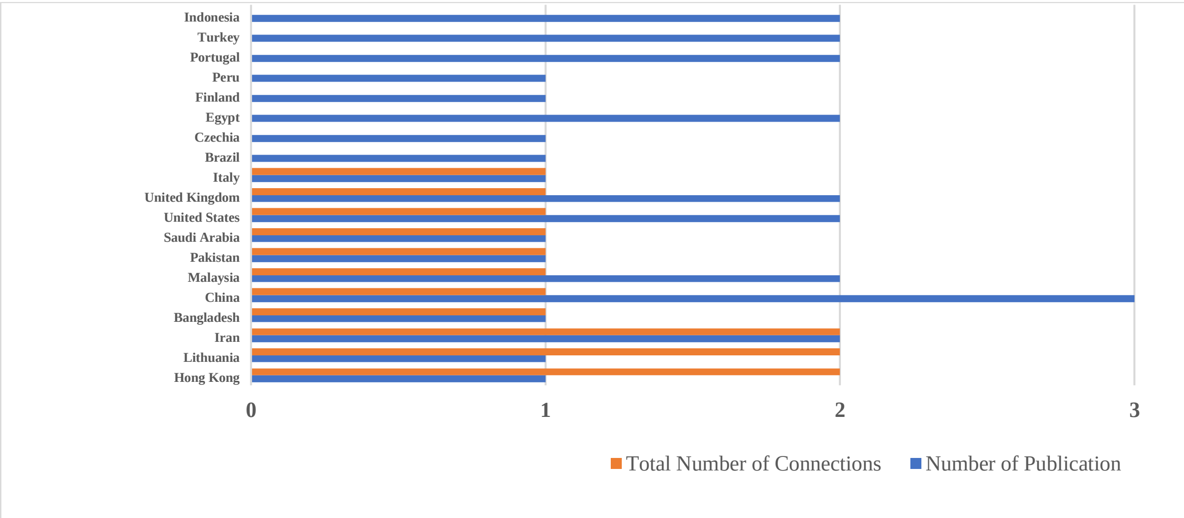

Figure 3: The total number of connections and publications for each country.

Figure 4, displays the organizations that contribute to the field through their scientific publications and have the most connections. Universities in Hong Kong, Lithuania, and Iran have the strongest collaboration, each with three links. These findings are consistent with those in Figure 2.

Figure 5, provides a graphical representation of the number of publications and connections between institutions.

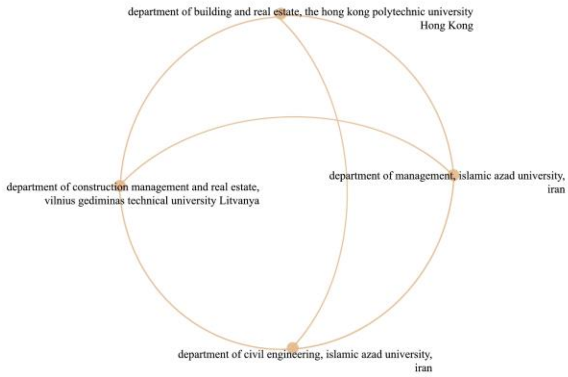

Figure 4: Institutions with the greatest number of connections.

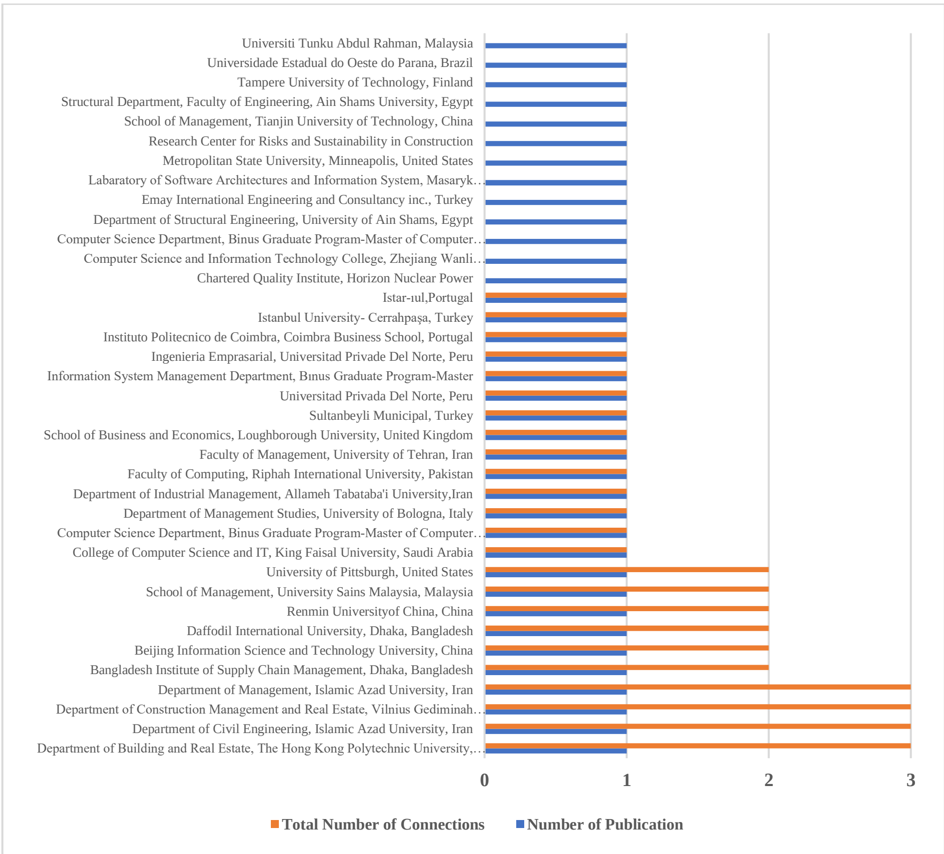

Figure 5: The total number of connections and publications for each institution.

Keyword Co-Occurrence Analysis

The study utilized VOSviewer software to conduct keyword analysis on 25 publications. The findings are presented in Figure 6, where node size represents keyword frequency, and line thickness indicates relationship strength. Node proximity indicates a strong relationship between keywords.

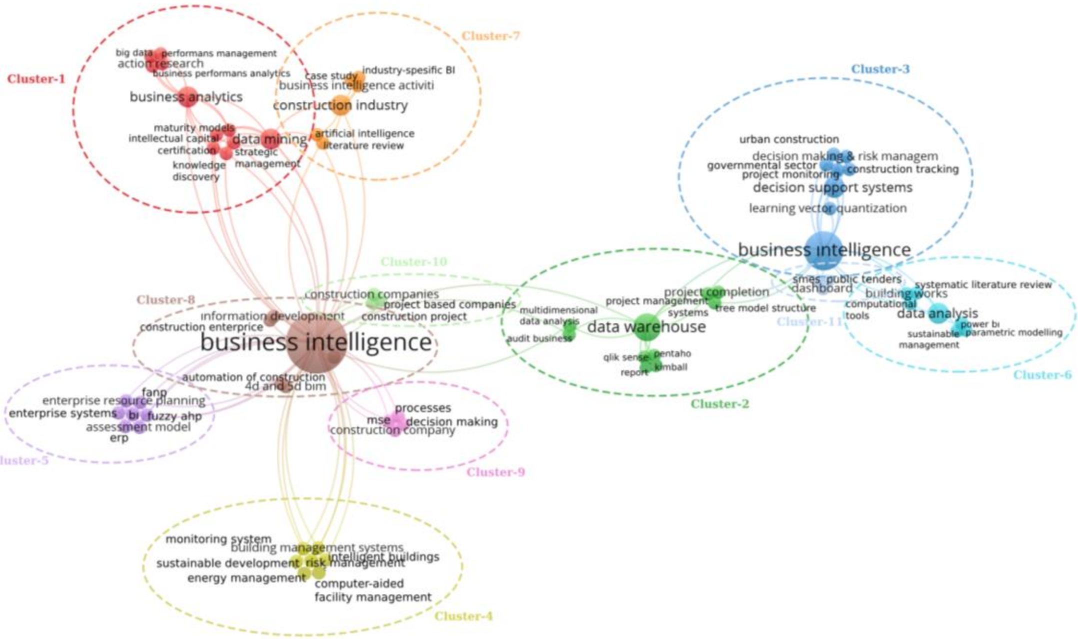

Figure 6: Illustration of keywords analysis.

Table 3, displays the seven keywords with the highest co-occurrence values, along with their total link strength and cluster numbers. The business intelligence keywords from Cluster-3 and Cluster-8 in Figure 6 are presented separately in the VOSviewer program due to the letter difference. To avoid repetition, two business intelligence phrases were merged in Table 3 to clean the data. These keywords represent popular research areas that are highly relevant and strongly linked to other related topics.

In Table 3, the term 'business intelligence' has a high synchronicity value and link strength, as it is the main topic. Additionally, terms such as 'Business Analytics', 'Data Mining', and 'Data Warehousing' are associated with the use of business intelligence in the construction industry and exhibit high link strength, indicating their relation to research areas in other clusters. The results are expected since Business Analytics is often used synonymously with Business Intelligence, while Data Mining and Data Warehousing are concepts related to business intelligence. Additionally, among the other terms listed in Table 3, Decision Support Systems are considered the most beneficial for business intelligence. The term Construction Industry directs the research towards the construction industry. Data analysis is the process of collecting and analysing data prior to visualization, with the goal of supporting decision-making in business intelligence.

Table 3. Seven keywords with the highest co-occurrence.

Keywords	Occurrences	Total Link Strength	Cluster No
Business Intelligence	15	59	Cluster- 8/3
Business Analytics	2	11	Cluster- 1

Data Mining	2	11	Cluster- 1
Data Warehouse	3	11	Cluster- 2
Decision Support Systems	2	8	Cluster- 3
Construction Industry	2	7	Cluster- 7
Data Analysis	2	7	Cluster- 6

Conclusion

The use of business intelligence has numerous benefits, including increased productivity, improved decision-making quality, reduced costs, increased profitability, and enhanced competitiveness. However, the construction industry is behind other industries in the use of Business Intelligence. This study conducted a bibliometric analysis on the use of business intelligence in the construction industry using Vosviewer software and publications from the Scopus database. The bibliometric analysis conducted in this study revealed only 25 publications on the use of business intelligence in the construction industry. Furthermore, there is no linear increase in the number of publications on this subject between 2007-2023. The limited number of citations, lack of focus on specific countries and organizations, and superficial terms of the subject in the keyword analysis showed no orientation towards the use of business intelligence in the construction industry. Given the potential benefits of business intelligence, it is essential for the construction industry, which has traditionally been slow to adopt technology, to embrace this field. This study aimed to increase awareness of the use and potential benefits of business intelligence in the construction industry, as well as to direct the industry towards its implementation. Future studies should include surveys and/or interviews with industry professionals to increase awareness of business intelligence further.

References

Delgado, J. M. D., Oyedele, L., Ajayi, A., Akanbi, L., Akinade, O., Bilal, M., & Owolabi, H. (2019). Robotics and automated systems in construction: understanding industry-specific challenges for adoption. *Journal of Building Engineering*, *26*, 100868.

Furmankiewicz, J., Furmankiewicz, M., & Ziuziański, P. (2015). Implementation of business intelligence performance dashboard for the knowledge management in organization. *Zeszyty Naukowe. Organizacja i Zarządzanie/Politechnika Śląska*.

Golestanizadeh, M., Sarvari, H., Chan, D. W., Banaitienė, N., & Banaitis, A. (2023). Managerial opportunities in application of business intelligence in construction companies. *Journal of Civil Engineering and Management*, *29*(6), 487-500.

Grant, M. J., & Booth, A. (2009). A typology of reviews: an analysis of 14 review types and associated methodologies. *Health Information & Libraries Journal*, *26*(2), 91-108.

Kiani Mavi, R., & Standing, C. (2018). Cause and effect analysis of business intelligence (BI) benefits with fuzzy DEMATEL. *Knowledge Management Research & Practice*, *16*(2), 245-257.

Lago, E. V., & Cantero, L. M. G. (2013). Business intelligence system to support the decision making process. *Revista Ingeniería UC*, *20*(3), 25-34.

Lopes, A. B., & Boscarioli, C. (2021). Business intelligence and analytics to support management in construction: a systematic literature review. *Revista Brasileira de Computação Aplicada*, *13*(1), 27-41.

Lu, Y., Li, Y., Skibniewski, M., Wu, Z., Wang, R., & Le, Y. (2015). Information and communication technology applications in architecture, engineering, and construction organizations: a 15-year review. *Journal of Management in Engineering*, *31*(1), A4014010.

Mandičák, T., Behúnová, A., & Mesároš, P. (2016). Impact of implementation and use of business intelligence on cost reducing in construction project management. *Acta Tecnología*, *2*(3), 5-11.

Mok, K. Y., Shen, G. Q., & Yang, J. (2015). Stakeholder management studies in mega construction projects: a review and future directions. *International Journal of Project Management*, *33*(2), 446-457.

Nithya, N., & Kiruthika, R. (2021). Impact of business intelligence adoption on performance of banks: a conceptual framework. *Journal of Ambient Intelligence and Humanized Computing*, *12*(2), 3139-3150.

Oliveira, J. F., Simões, R., & Pedrosa, I. (2021). The application of dashboards in the management of commercial proposals to public tenders: application to SMEs in the civil construction sector. *Proceedings of 16th Iberian Conference on Information Systems and Technologies*, pp. 1-5.

Petrini, M., & Pozzebon, M. (2009). Managing sustainability with the support of business intelligence: integrating socio-environmental indicators and organizational context. *The Journal of Strategic Information Systems*, *18*(4), 178-191.

Pollack, J., & Adler, D. (2015). Emergent trends and passing fads in project management research: a scientometric analysis of changes in the field. *International Journal Of Project Management*, *33*(1), 236-248.

Raffoni, A., Visani, F., Bartolini, M., & Silvi, R. (2018). Business performance analytics: exploring the potential for performance management systems. *Production Planning & Control*, *29*(1), 51-67.

Sardroud, J. M. (2015). Perceptions of automated data collection technology use in the construction industry. *Journal of Civil Engineering and Management*, *21*(1), 54-66.

Van Eck, N. J., & Waltman, L. (2012). *VOSviewer manual* (Version 1(0)).

Viljamaa, E., & Peltomaa, I. (2014). Intensified construction process control using information integration. *Automation in Construction, 39*, 126-133.

Vuori, V. (2007). Business intelligence activities in construction companies in Finland–a series of case studies. *Proceedings of the 8th European Conference of Knowledge Management*, pp. 1086-1092.

Financial Resilience: Challenges for SME's During the Crisis

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Abstract

Unforeseen events such as global recessions, natural disasters, geopolitical conflicts, or pandemics can have widespread economic consequences. Financial instability, especially for small and medium-sized enterprises, might be considered as the common reason for business failures. Financial resilience refers to an organization's ability to withstand and recover from a crisis and consequently prevent business failure. By prioritizing financial resilience, construction companies can enhance their operational ability. However, research on financial resilience of small and medium-sized enterprises in the construction sector is limited. This study aims to examine the difficulties encountered in ensuring the financial resilience of small and medium-sized enterprises in the construction sector. In this study, the challenges experienced by these enterprises were examined through bibliometric analysis and presented as systematic literature review to develop a proactive attitude towards crises. Bibliometric analysis is carried out for author & publication analysis and science mapping purposes. In this study, citation and timeline analysis were attached to this analysis. To explore and visualize the relationships, innovative literature mapping tools, Connected Papers and Research Rabbits, were used. In the review, the difficulties experienced by small and medium-sized businesses during the crisis were grouped in the areas of credit, project development, cost, and supply chain management. The outcome of the review indicates that the most common difficulties against financial resilience are cost, credit, and supply chain problems. The creative review approach can contribute to existing knowledge and serve as a reference for future research in this study.

Keywords: *construction, economic crisis, financial resilience, small and medium-sized enterprises.*

Introduction

Catastrophic events such as recessions and pandemics might be tough for small and medium-sized enterprises (SMEs) in terms of financial instability. Financial instability for enterprises refers to a condition where a company experiences significant volatility, uncertainty, or vulnerability in its financial position, operations, or market standing, potentially jeopardizing its ability to meet financial obligations or sustain profitable performance over time (Minsky, 1977). In addition, it can be defined as a reason for business failures. To avoid failures, providing resilience is essential for mitigating the effects of instability and ensuring the long-term sustainability and success of enterprises. Financial resilience for enterprises encompasses the ability of a business to navigate through financial challenges, uncertainties, and disruptions while maintaining its stability, continuity, and capacity for growth (Rausch & Sommer, 2017).

Financial resilience is paramount for small and medium-sized enterprises (SMEs) due to several key reasons: survival, adaptability, access to funding, operational stability, risk management, and long-term growth (Diamantidis & Diamantidis, 2018). Recent studies show that in many countries, construction organizations are characterized as small organizations or small and medium enterprises (SMEs) (PwC-PricewaterhouseCoopers, 2011; Hatton et al., 2012). The construction industry has a significant role in the overall economy as small and medium enterprises (SMEs). It is large and responsive, as well as having a strong linkage with other industries; it is a key sector that can affect economic development and activities (Dudayev & Ismail, 2012). In addition, the construction industry tends to account for between 4 and 10 percent of an economy's gross domestic product (GDP) (Wilkinson et al., 2015). Besides, the construction sector provides the essential requirements of human beings, such as shelter and infrastructure. In this context, it contributes to the creation of a built environment and reconstruction after disasters. These factors make the construction organizations' financial resilience, defined as small and medium enterprises (SMEs), significant. It is important to define the challenges to providing financial resilience for SMEs. The challenges faced by SMEs in the construction sector during the crisis are multifaceted. SMEs in construction, like other sectors, are significantly affected by the COVID-19 pandemic (Thukral, 2021). Another crisis for SMEs could be the financial crisis of 2008. Limited access to finance or credit remains a major issue for SMEs that increases their vulnerabilities in the crisis (Vasilescu & Sitnikov, 2022). For instance, the pandemic has brought about uncertainties in maintaining business continuity, leading to financial and operational disruptions (Zutshi et al., 2021). Hu and Kee (2021) identified specific challenges that include financial impacts, supply chain disruptions, and changing business environments. Additionally, SMEs in construction face challenges related to operational costs (Mendy, 2022). Nguyet (2023) analyzed the financial resilience of British SMEs during the financial crisis of 2008 and defined the challenges of bank loan dependence, a lack of diverse financing, and the need for stable financing strategies from policymakers. Besides, it is found that the financial resilience of SMEs is affected positively by a supplier network, profitability, internal equity, and diversity of financing but negatively by bank loan dependence. In addition, effective project development strategies affect the financial resilience of construction companies (Paranchuk et al., 2022). To address the challenges, SMEs in construction must focus on financial stability, supply chain management, operational costs, and sustainable business practices in terms of financial resilience. In this context, this research aims to identify the difficulties for SMEs in construction during the crisis through a literature review. For this purpose, to define the challenges, Web of Science and ProQuest databases were used. The abstracts were evaluated in the first stage. After that, according to this review, the main challenges were identified in the areas of cost, credit, project development, and supply chain management through bibliometric analysis. In the next step, to explore the relationship between these areas, innovative literature mapping tools, Connected Papers and Research Rabbits, were used. In the conclusion, the outcomes of these mappings were discussed. Recommendations were presented in the discussion.

Literature Review

Financial resilience is crucial during crises such as the COVID-19 pandemic, the 2008 global recession, currency devaluations, environmental crises, natural disasters, and political conflicts. Financial resilience for a company refers to its ability to withstand and recover from economic shocks (Tolner et al., 2023). Financial resilience for small and medium-sized enterprises (SMEs) is significant for their sustainability and success in the ever-changing business landscape. Within the context of the European Union, SMEs are defined as companies with fewer than 250 employees and/or turnover less than €50 million. Their impact upon the EU economy is high considering that "SMEs represent 99% of all businesses in the EU" (European Commission, 2012). Their vulnerability arises virtually by definition because of the small scale of their human and financial resources (Bannock, 2004). Despite the relevance of SMEs to the economy, Kamalahmadi and Parast (2016) noted there is "a very limited scholarly work on resilience practices in SMEs" and a limited understanding of "how organizations, particularly SMEs, can achieve degrees of resilience" (Bhamra et al., 2011). Since there are many SMEs in the construction industry, it is important to examine this issue. During the crisis, SMEs in the construction sector faced various challenges. The critical challenges can be defined as cost and finance-related (Zutshi et al., 2021), access to credit (Wehinger, 2014; Balogun et al., 2018), project development (Visinescu & Micuda, 2009), supply chain disruptions (Hu & Kee, 2021), labor market (Dainty et al., 2005), marketing (Ganah et al., 2008), and evolving business environments (Thukral, 2021).

Method

To comprehend the financial resilience of construction SMEs, it is imperative to delineate the challenges encountered and the corresponding responses to unforeseen crises. For this aim, a bibliometric analysis was conducted to identify the challenges, and this study's methodology is presented as a literature review. For the review, the research process was divided into four parts, Web of Science and ProQuest databases were used. In the first part of the process, "financial resilience," "construction," "SME," "challenge," and "crisis" keywords were searched to perceive the overall perspective on financial resilience in construction. Besides, at this stage, the abstracts were examined. According to this, the main challenges were defined in groups that include cost overruns, access to credit, project development, supply chain disruptions, labor market, marketing, and evolving business environments. As it can be seen in Figure 1, the research was deepened, and the common challenges were reidentified as cost overruns, access to credit, project development, and supply chain disruptions in the second step. In addition, these challenges' details were explained in this process. In the third stage, to explore and visualize the relationships between the challenges and studies, innovative literature mapping tools, Connected Papers and Research Rabbits were used and presented. In the last stage of the research, the discussion was carried out as results, and for further research, recommendations were suggested.

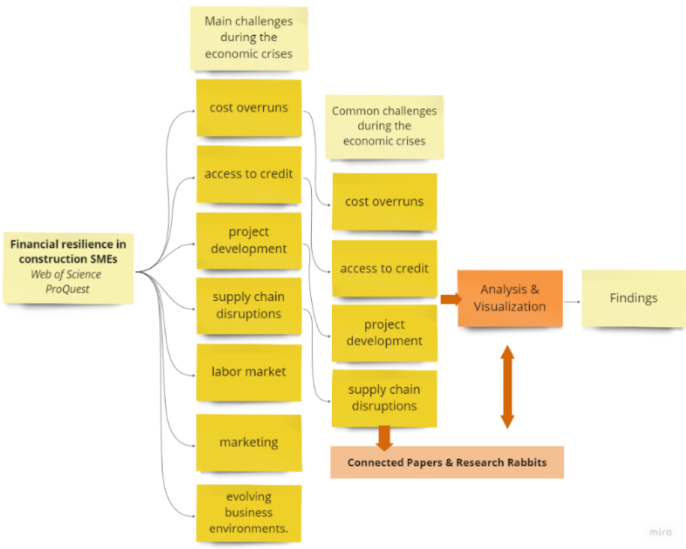

Figure 1: Research method.

Findings

The common challenges were examined in the second step of the work. For this step, bibliometric analysis was conducted through Connected Papers. The findings were presented as clusters. To understand the relationship between the clusters, they were combined and visualized by including authors and citations by Research Rabbit in the third step. This visualization can be seen in Figure 2. Before the visualization of the work, the clusters were presented as below.

Challenges of Accessing Credit

During crisis times, finding alternative financial sources is vital for construction SMEs. In a financial crisis such as the Financial Crisis of 2008, obtaining bank loans or credit was an important problem for companies and individuals. Alternative sources of external financial facilities for SME's varied across trade credit to bank loans. While credit-constrained institutions mainly depend on trade credits, unconstrained SMEs heavily depend on bank loans (Carbó-Valverde et al., 2016). This indicates that trade credit is crucial during times of crisis. The limitation of financial resources is a factor that negatively affects risk adaptation (Crick et al., 2018). Balogun et al. (2018) identified several factors that are preventing SMEs and contractors from accessing credit from financial institutions, such as lack of collateral, high interest rates and bank changes, lack of owner's contribution, lack of good business plan development, lack of excellent managerial skills, lack of business skills, and lack of binding building contact agreements. In addition, they proposed a conceptual framework for credit accessibility among construction SMEs. Lafuente (2017) found that trade credit from suppliers and bank diversification positively impact performance, particularly during economic downturns. In addition, there are a few main challenges to accessing credit at the usual times. The Organization for Economic Cooperation and Development (OECD) (2006) argues that the difficulties that SMEs encounter when trying to access financing can be due to an incomplete range of financial products and services, regulatory rigidities or gaps in the legal framework, or a lack of information on both the banks and the SME's side. Banks may avoid providing credit to certain types of SMEs, in particular, very young firms in the construction industry. In addition, during crisis times, the rate of interest might be at a very high level. These factors illustrate the challenges SMEs face to survive.

Supply Chain Disruptions as a Challenge

In the construction sector, supply chains are complex and dynamic and involve numerous stakeholders, such as suppliers, manufacturers, subcontractors, logistics providers, and regulatory bodies. Since the supply chain has a complicated network, efficient management is significant to minimize costs, optimize project performance (Seuring & Müller, 2008), and manage risks (Roshdi, 2023). During crisis times, because of the various stakeholders, the effects of the crisis may spread and increase in severity. That's why the supply chain network should be observed and managed in a proactive way, especially before a crisis. Supply chain difficulties faced by construction SMEs during a crisis include interruptions in operations leading to liquidity problems, challenges in maintaining jobs, and limited access to government support (Sawant et al., 2022). Besides, the balance of supply and demand may change, as may the price fluctuations of the production of the construction materials. The supply chain network may have international subcontractors or providers. This makes political conflicts vital for construction SMEs. A political conflict in the country can be transformed into a macro-crisis in the project. In recent years, as a force majeure, the COVID-19 pandemic has significantly impacted global supply chains, particularly SMEs due to their sensitivity to external threats and disruptions (Saeedi et al., 2022). Abidin and Ingirige (2018) investigated the supply chain's critical vulnerabilities and capabilities that formulate the level of resilience in handling disruptive events in construction projects. The findings revealed that the top five critical vulnerability factors in the supply chain include political or regulatory changes, market pressures, management, financial, and strategic vulnerability. All these challenges highlight the importance of resilience and effective supply chain management strategies for SMEs in the construction industry to navigate different crises successfully.

Challenges of Cost Overruns

Construction project cost overruns occur when the actual costs of completing a project exceed the initially estimated budget. Several factors contribute to these overruns, including inaccurate initial cost estimates, unforeseen changes in project scope or design, fluctuating material and labor costs, delays in project completion, and ineffective project management practices. (Flyvbjerg et al., 2002). Besides, unforeseen events, such as the COVID-19 pandemic, significantly impact cost overruns in construction SMEs (Adepu et al., 2023; Gamil, 2020). The pandemic led to delays in various projects, escalating material prices, increased demand from suppliers, and financial implications, all contributing to cost overruns (Rashidah & Nasır, 2022). Another crisis, such as a financial crisis like the one faced by Iraq in 2014, can have a profound effect on construction activities, leading to insolvency issues, project delays, and cost overruns (Fadhil & Burhan, 2022; Haider et al., 2022). All these factors can cause cost overruns in construction projects. This increase is vital for small companies in the construction industry and affects their survival and resilience.

Challenges for Project Development

The rate of demand for real estate may change for investors in the crisis. According to the demand analysis, the early stages of project development and construction may be stopped. Also, the preferences may cause the need for different types of real estate. The COVID-19 pandemic can be an example of this situation. The pandemic caused a change in preference, and this led to increased interest in properties with outdoor amenities like gardens or balconies (Stachura & Jagiello-Kowalczyk, 2023). This affected the development of projects in terms of building typologies. It can be inferred that crises can affect the relationship between supply and demand from the perspective of construction SMEs and investors. Additionally, crises significantly impact existing project development in construction by causing disruptions, financial losses, and delays. From this perspective, Thukhal (2021) stated that COVID-19 impacts project development in construction SMEs due to sector vulnerability. Creativity, resilience, and government support are vital for SME survival and project continuity in uncertain times.

Visualization of the Clusters

To perceive the relationship between clusters that explain the challenges, the citation network and timeline mappings were created by Research Rabbit. Research Rabbit is an innovative mapping software for literature reviews.

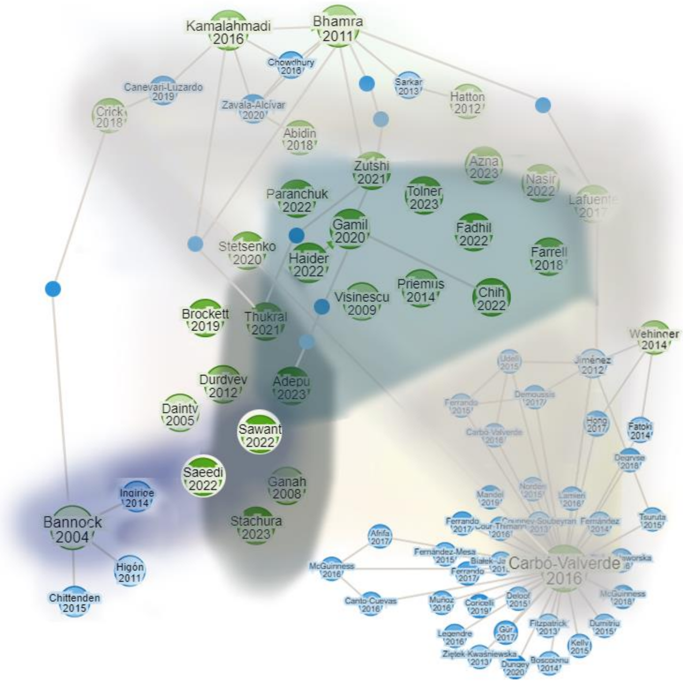

Figure 2: Visualization of the clusters.

Besides, it is a research platform that is based on Semantic Scholar. The difference between Research Rabbit and the existing visualization tools is to create online collections, set alerts for newly published papers, and get personalized recommendations for the relevant works. Because of these new features, this online platform was chosen for the analysis and visualization. To create Figure 2, a collection was created by the Web of Science and ProQuest databases.

In Figure 2, green nodes show the main resources in the research collection, while blue dots indicate the suggested works for the collection. The size of the nodes represents the number of citations. The citation network between the nodes can be seen in this figure. Besides, the clusters' relationships were demonstrated by colors. A grey color was used for the first cluster, which is "**Challenge about Accessing Credit**." According to the size of the color, there are many studies on this subject. Dark gray shows "**Supply Chain Disruptions as a Challenge**." The size of this color emphasizes the lack of work on the topic. Light green presents the cluster "**Challenge about Cost Overrun**," while dark blue expresses the "**Challenge for Project Development**." The size of light green is larger than dark blue, this shows the areas that need development. So, by these colors' size, the benchmarking can be conducted rapidly. Another finding is to investigate the timeline of the papers. This timeline is shown in Figure 3.

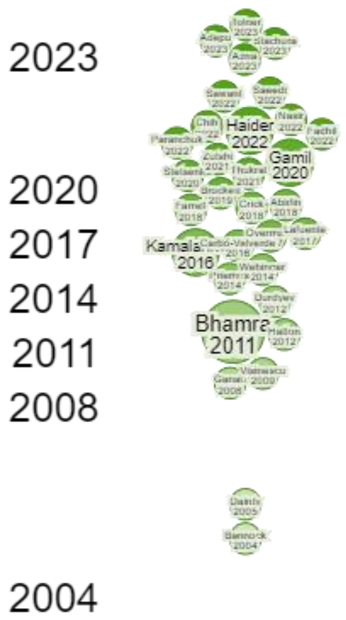

Figure 3: Timeline of the papers.

According to Figure 3, the earlier works were started in the 2000s. It can be related to the financial crisis of 2008. Moreover, the year of the COVID-19 pandemic can be evaluated as another turning point for the studies. Besides, the size of the nodes shows the number of citations. Regarding this, Bhamra (2011), Kamalahmadi and Parast (2016), Gamil (2020), and Haider (2022) can be interpreted as worthful studies in the literature.

Conclusion and Discussion

Financial resilience in construction can be defined as the capability of construction firms to resist and recover from financial challenges, shocks, and operational disruptions. To ensure resilience, the challenges must be examined in detail. In this study, two different databases were evaluated through the abstracts. According to the abstracts, the results were classified as clusters. The common challenges were defined as cost- and finance-related, access to credit, project development, and supply chain disruptions. These clusters were analyzed and visualized by Connected Papers and Research Rabbit platforms. Through these two innovative platforms, different relationships were investigated and defined as citation networks. Besides, regarding colors, benchmarking was conducted in this research area. According to this, the cluster "Challenge about Accessing Credit" has the highest number of studies. The cluster "Challenge for Project Development" has the lowest number of works. As specified by the timeline, it can be inferred that this research area was started in the 2000s during the financial crisis of 2008. In addition, it can be seen that the studies intensified during the COVID period. In this literature review, an extensive perspective was presented about the challenges facing construction SMEs.

For further works, according to the analysis, clusters with a low number of studies, "challenge of project development or supply chain during the crisis," may be selected for the construction SMEs.

References

Abidin, N. A., & Ingirige, B. (2018). The dynamics of vulnerabilities and capabilities in improving resilience within Malaysian construction supply chain. *Construction Innovation: Information, Process, Management*, *18*(4), 412-432. https://doi.org/10.1108/CI-09-2017-0079

Adepu, N., Kermanshachi, S., Pamidimukkala, A., & Loganathan, K. (2023). Analysis of the factors affecting construction project cost during COVID-19. doi: 10.1061/9780784484883.062

Balogun, O. A., Ansary, N., & Agumba, J. N. (2018). Identification factors influencing accessibility of credit for small and medium contractors in the construction industry. doi: 10.3311/CCC2018-069

Bannock, G. (2005). The economics and management of small business: An international perspective. London: Taylor & Francis Routledge.

Bhamra, R., Dani, S., & Burnard, K. (2011). Resilience: The concept, a literature review and future directions, *Int. J. Prod. Res*., *49*(18), 5375–5393.

Carbó-Valverde, S., Rodríguez-Fernández, F., & Udell, G. F. (2016). Trade credit, the financial crisis, and SME access to finance. *Journal of Money, Credit and Banking*, *48*(1), 113–143. https://doi.org/10.1111/jmcb.12292

Crick, F., Eskander, S. M. S. U., Fankhauser, S., & Diop, M. (2018). How do African SMEs respond to climate risks? Evidence from Kenya and Senegal. *World Development, 108*, 157–168. https://doi.org/10.1016/j.worlddev.2018.03.015

Dainty, A. R. J., Ison., S. & Briscoe, G. H. (2005). The construction labour market skills crisis: The perspective of small–medium-sized firms. *Construction Management and Economics*, doi: 10.1080/0144619042000326738

Diamantidis, A., & Diamantidis, A. (2018). The impact of financial management practices and financial attitudes on the financial resilience of small and medium-sized enterprises during an economic crisis. *Journal of Applied Accounting Research, 19*(3), 400-416.

Durdyev, S., & Ismail, S. (2012). Role of the construction industry in economic development of Turkmenistan. *Energy Education Science and Technology Part A: Energy Science and Research*, *29i*, 883-890.

European Commission. (2012). What is an SME?. [Online]. Available: https://ec.europa. eu/growth/smes/business-friendly-environment/smedefinition_ en Accessed on: Apr. 08, 2024.

Fadhil, G. A., & Burhan, A. M. (2022). Developing crisis management system for construction projects in Iraq. *Journal Engineering*, doi: 10.31026/j.eng.2022.01.03

Flyvbjerg, B., Holm, M. K. S., & Buhl, S. H. (2002). Underestimating costs in public works projects: Error or lie?, *Journal of the American Planning Association*, *68*(3), 279-295.

Gamil, Y., & Alhagar, A. (2020). The impact of pandemic crisis on the survival of construction industry: A case of COVID-19. *Mediterranean Journal of Social Sciences*, doi: 10.36941/MJSS-2020-0047.

Ganah, A., Pye, A., & Walker, C. (2008). Marketing in construction: Opportunities and challenges for SMEs.

Haider, F., Bhatti, S., & Siddiqui, U. A. (2022). Construction delays and project failures due to the biological pandemic of Covid-19 and lockdown effects. Sir Syed University research, *Journal of Engineering and Technology*, doi: 10.33317/ssurj.287.

Hatton, T., Seville, E., & Vargo, J. (2012), Improving the resilience of SMEs: Policy and practice in New Zealand, *Resilient Organizations Research Report 2012/012 October 2012*, Resilient Organizations, Canterbury.

Hu, M. K., & Kee, D. M. H. (2022). SMEs and business sustainability: Achieving sustainable business growth in the new normal. *In Research Anthology on Business Continuity and Navigating Times Of Crisis* (pp. 1036-1056). IGI Global.

Kamalahmadi, M., & Parast, M. M. (2016). A review of the literature on the principles of enterprise and supply chain resilience: Major findings and directions for future research, *Int. J. Prod. Econ.*, *171*, 116–133.

Mendy, J. (2022). Systematizing body of knowledge on business challenges and strategizing post COVID-19. *Advances in Logistics, Operations, and Management Science Book Series*, doi: 10.4018/978-1-7998-8856-7.ch011.

Minsky, H. P. (1977). Financial instability and the role of monetary policy. *The American Economic Review*, *67*(2), 326-335.

OECD (Organization for Economic Cooperation and Development). (2006). The SMEs financing gap, Volume 1: Theory and evidence. Paris: OECD Publishing.

Paranchuk, S., Chervinska, O., Popadynets, N. M., & Kornachuk, O. Y. (2022). Financial resources of construction companies in crisis conditions. *Regional Economy*, doi: 10.36818/1562-0905-2022-2-8.

PwC-PricewaterhouseCoopers. (2011). Valuing the role of construction in the New Zealand economy. (accessed 10 April 2024).
www.constructionstrategygroup.org.nz/downloads/PwC%20Report%20%20Construction%20Sector%20Analysis%20Final%204%20Oct.pdf

Rashidah, S., Nasir, M., Hasim, S., Ja'afar, M. S., & Ali, M. A. S. M. (2022). Escalation of project cost due to Covid-19 pandemic. *Proceedings of International Structural Engineering and Construction*, doi: 10.14455/isec.2022.9(2). cpm-03.

Rausch, A., & Sommer, L. (2017). Financial resilience in small and medium-sized enterprises: A conceptual analysis, *International Journal of Business and Management*, *12*, 92-105.

Roshdi, F. R. M. (2023). The supply chain management mechanism for materials procurement in the construction industry. *International Journal of Academic Research in Business & Social Sciences*, doi: 10.6007/ijarbss/v13-i3/16645.

Saeedi, S., Koohestani, K., Poshdar, M., & Taleb, S. (2022). Investigation of the construction supply chain vulnerabilities under an unfavorable macro-environmental context. *Annual Conference of the International Group for Lean Construction*, doi: 10.24928/2022/0190.

Sawant, R., Joshi, D. A., & Menon, R. (2022). Blockchain technology in construction supply chain management during pandemic: A bibliometric analysis and systematic literature review. *2022 International Conference on Computing, Communication, and Intelligent Systems (ICCCIS)*, doi: 10.1109/ICCCIS56430.2022.10037673.

Seuring, S., & Müller, M. (2008). From a literature review to a conceptual framework for sustainable supply chain management. *Journal of Cleaner Production*, *16*(15), 1699-1710.

Stachura, E., & Jagiello-Kowalczyk, M. (2023). Housing and the pandemic: How has Covid-19 influenced residents’ needs and aspirations?. *Real Estate Management and Valuation*, doi: 10.2478/remav-2023-0010.

Thukral, E. (2021). COVID-19: Small and medium enterprises challenges and responses with creativity, innovation, and entrepreneurship. *Strategic Change*, doi: 10.1002/JSC.2399.

Tolner, F., Barta, B., & Eigner, G. (2023). Economic resilience and antifragility: Classification of SMEs’ shock reactions based on balance sheet and income statement data. doi: 10.1109/SACI58269.2023.10158644.

Visinescu, S., & Micuda, D. (2009). Challenges faced by EU SMEs in the context of the global economic crisis. *Romanian Economic and Business Review, 4*(3), 187-198.

Wehinger, G. (2014). SMEs and the credit crunch: Current financing difficulties, policy measures and a review of literature. *Oecd Journal: Financial Market Trends, 2013(2)*, 115-148. doi: 10.1787/FMT-2013-5JZ734P6B8JG.

Zutshi, A., Mendy, J., Sharma, G. D., Thomas, A., & Sarker, T. (2021). From challenges to creativity: Enhancing SMEs’ resilience in the context of COVID-19. *Sustainability*, doi: 10.3390/SU13126542.

Micro-Sized AEC Firms' Economic Strategies for Firm Survival in Uncertain Economic Conditions

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Abstract

According to the December 2023 report of the Turkish Statistical Institute, micro-scale enterprises constituted 90.6 percent of the total number of enterprises. Micro-enterprises employ fewer than ten persons whose annual turnover or balance sheet total does not exceed 10 million Turkish Liras. According to the Central Bank of Türkiye reports for 2020, construction companies constitute 14.76%, and the number of employees in the sector constitutes 9.91% of Türkiye in general. The Turkish construction sector has been adversely affected by epidemics, regional wars, the migrant crisis, earthquakes, inflation, and exchange rate increases. Research mentioned that micro-sized companies can survive in uncertain economic conditions due to their innovative and flexible structures. This study investigated the survival strategies of micro-scale architecture, engineering, and construction firms (MSAECFs) under uncertain economic conditions. Survival strategies were screened from the existing literature through a systematic search. In the second stage, the current situation was determined by conducting semi-structured, in-depth interviews with micro-scale companies from the Turkish construction sector. As a result of the research, the survival strategies used by micro-scale AEC companies are as follows: Broadening stakeholder networks for new clients and projects, strengthening relationships with suppliers/sub-contractors for the increase of the quality and decrease of the costs, diversifying into new markets, countries, and regions, advertising through social media, web, and print publications to get new projects.

Keywords: *construction sector, architecture engineering construction (AEC) firms, micro-sized firms, economic conditions, survival strategies.*

Introduction

While the contraction in the construction sector has become evident since 2018 due to the impact of domestic and international economic developments, the problems increased with the COVID-19 epidemic. Then, the loss of momentum continued with the transition to tight monetary policy in the economy. The sector grew, albeit very limited, in the first half of 2021, in parallel with the recovery process from the epidemic. However, it has started to contract again with the developments in the global and national economies. As a result of these developments, the construction sector contracted by 0.6% and 7.1% in 2021 and 2022, respectively. Increasing construction activities due to the impact of devastating earthquakes centered in Kahramanmaraş and Hatay in the first half of 2023 caused the outlook in the sector to turn positive. Compared to the same period of the previous year, the growth recorded in the industry in the April-June 2023 period stood out as the fastest increase in the last 21 quarters. The increasing demand for urban transformation in cities with high earthquake risk, especially in Istanbul, has created potential in the housing field for the coming period. In addition, it is thought that the financial support programs developed by the state for urban transformation projects will affect this situation positively.

These fluctuations in the Turkish economy affect micro-scale companies (enterprises with less than ten annual employees and whose annual net sales revenue or financial balance sheet is at most ten million Turkish Liras) at the first stage. Among the reasons why micro-sized companies are affected by economic fluctuations at the first stage is that they do small-scale business due to the small size of the companies; if they do not specialize in a niche area, there is no share left for micro-sized companies in the shrinking market, and their customer portfolio is narrow. In addition to these negative aspects, micro-scale companies also have an essential financial advantage in that they adapt to current market conditions much more quickly than larger-scale companies with the flexible structures that they gain from being small-scale organizations. Micro-scale architecture, engineering, and construction firms (MSAECFs) are resilient in uncertain economic conditions with flexible and innovative structures. These positive and negative aspects of micro-scale companies constitute the factors that cause companies to succeed or fail in periods of economic fluctuations and or recessions. ("Building an Innovation Strategy for SMEs: An Analysis of the Construction Industry in Turkey," 2019; Chih et al., 2022; Danforth et al., 2017; Okudan et al., 2022; Oviedo-Haito et al., 2014; Tummalapudi et al., 2020, 2021; Ulubeyli et al., 2018)

This study aims to determine the best practices in business strategies of micro-sized AEC companies that have managed to survive economic fluctuations and recessions and to set an example for micro-sized companies in the sector. To achieve this goal, studies in the field were researched through a literature review, and then interview questions were created for micro-sized companies using these studies. Afterward, meetings were held with micro-scale AEC companies in Istanbul. Finally, the interview results were compared with the literature. This study is a preliminary pilot study of a more extensive study.

Literature

The construction industry affects both the economies of countries and the global economy. The construction industry may experience some bottlenecks with the changes in the country and world economies. Bottlenecks and uncertain economic conditions also affect companies' decisions to build/not build or to bid/submit (Arıcı Üstüner & Balaban Ökten, 2022; Li et al., 2020; Adabre et al., 2022). In the foreign construction sector literature, studies have examined the measures to be taken during the economic crises and companies' reactions to the situation during these periods. These studies have shown that the demand for production in the sector naturally decreases during crises in the construction sector. Research has shown a 75% decrease in housing construction in European countries during the economic crisis 2007. In public sector projects, this rate is around 67% (Oviedo-Haito et al., 2014). It was observed that more than 170,000 small-scale construction companies were closed during the same year's economic crisis in the USA. These crises cause bankruptcies, job losses, and economic collapses. Uncertainties and fluctuations that occur in the economic cycle of a construction company cause the company to enter a natural learning period in this process. Suppose the companies that survive due to these economic fluctuations can integrate what they have implemented and learned in this process into the general structure of the company. In that case, the company is expected to overcome future economic fluctuations and bottlenecks more easily (Danforth et al., 2017). In the research conducted by Danforth et al. (2017) on the subject, it was seen that construction companies exhibited two types of behavior in economic problems. The first is short-term solutions, and the other is long-term paradigm changes within the scope of company principles. In another study, it was seen that companies applied three different strategies to economic problems. The first is the differentiation strategy from the sector where competition is high. This strategy adopts creating a unique product and investing in it. The second strategy is to reduce costs with the cost leadership strategy. The third and final strategy is targeting a specific market within the more significant construction industry (Tansey et al. 2013). In another study, Lim et al. (2010) state that contract-based measures are one of the strategies implemented by construction companies in economic bottlenecks. This strategy aims to enable more work to be done or reduce the work risks. Another strategy implemented in companies is cost control. In this strategy, companies appear to set rules such as reducing material losses, applying strict rules in tender criteria, and controlling money flows. Lim et al. (2010) include financial measures such as using companies' emergency reserves, cutting operating expenses, and taking advantage of loans. Although there are studies investigating the strategies to be implemented in economic bottlenecks in the construction industry, the strategies must be helpful and efficient for the companies. Bad strategies implemented during such crises will result in failure for companies (Tummalapudi et al., 2021). In times of crisis, companies need to quickly decide on their strategies and minimize crises in this way. In international studies, contract claims, legal disputes, cash flow problems, low-profit rates, and marketing difficulties are cited as why construction companies fail and cannot continue their existence during crises. All these problems affect each other during the crisis, causing a cycle (Tummalapudi et al., 2021). In this case, as mentioned before, it is essential that the company affected by the crisis chooses the right strategies and incorporates them into its business. The research indicates that more than 850,000 companies in the USA can be defined as small-scale construction companies (employing between 1-19 people). Large-scale companies' financial strength, capacity, and credit facilities are more solid and balanced. For this reason, small-scale companies will be most affected by economic bottlenecks and fluctuations (Tummalapudi et al., 2021).

Material and Method

In semi-structured and in-depth interviews, which are among the data collection methods, pre-prepared questions are asked to each participant in the same format and order. Still, other questions are also asked of the participants to obtain more detailed information based on the participants' answers to these questions. The sample to be used in this project will be selected through "convenience sampling" from companies that are members of the Turkish Contractors Association, the Turkish Chamber of Architects, and the Turkish Chamber of Civil Engineering, and those that meet the definition of "Micro-Scale" companies and have continued their existence during economic crises. In the convenience sampling type, researchers select the data to be evaluated in the sample frame without any design. This type of sampling is a method that speeds up research because it allows the researcher to act according to the situation that is close and easy to access.

Interviews were held with 9 AEC companies in January 2024. The interviews were conducted face to face with company owners. After asking general information questions about firms and the interviewed professionals, the following questions were asked to understand the business strategies used by micro-scale AEC firms during the economic crisis. Information about the interviewed firms is also given in Table 01.

- What strategies do you use to ensure your company can continue its economic activities?
- Which strategies have you used so far have been successful?
- Which ones failed?
- What do you think are the reasons for commercial success and failure in your commercial strategies?
- What business lessons have you learned while trying to improve your company's economic performance?

Table 1. Information on micro-sized AEC companies interviewed.

Firm No	Founding Date	Age of the Firm	Number of Employees	Services
Firm 01	2018	6	3	Architecture, Interior Design, Construction
Firm 02	2017	7	4	Architecture, Interior Design
Firm 03	2016	8	3	Architecture
Firm 04	2021	3	3	Architecture
Firm 05	2021	3	2	Architecture, Interior Design, Furniture Design, 3D photorealistic visualization.
Firm 06	2022	2	1	Architecture, Interior Design, Construction permit services, 3D photorealistic visualization.
Firm 07	2017	7	3	Architecture, Interior Design, 3D photorealistic visualization
Firm 08	2023	1	3	Architecture, Urban Design
Firm 09	2000	24	5	Architecture, Restoration, Construction

Results and Discussion

All nine interviewed companies stated that they developed their customer portfolio through acquaintances and that they always received new business through previous work they had done. Interviewees emphasized that quality work brings new business, and customer satisfaction is an important factor for business success. Firm 02-03 stated that the overlapping of economic crisis periods and election periods increased the impact of the economic crisis. They indicated that their offices work with municipalities, project decisions stop when the election period approaches, and the sector waits until after the elections. For this reason, Firm 02-03 stated that holding early elections negatively affects the market. Firm 03 stated that she has resisted providing only architectural services until now but has had financial difficulties for the last year and plans to offer other design-related services. It has been explained that the economic returns of long-term work in an inflationary environment are low, so inflation-related price increases required by this economic environment should be added to the contracts. It has been stated that employers also approve price revisions for periods such as six months or one year. Another strategy that companies use in long-term projects is to purchase all materials at the beginning of the project. In this way, they are not affected by fluctuations in material prices. This is, of course, valid for small and medium-sized construction works. It is stated that small-scale design works that are completed quickly are beneficial for companies to support themselves economically. Although the payments for small and fast jobs are also small, they meet the urgent economic needs of companies because their cash flow is rapid. For this reason, firms have developed new strategies to market products they can produce and deliver quickly. For this reason, Firm 05 said that they started doing furniture design work they had never planned to do. Firms that opened after 2020 use joint offices with other companies to reduce their general expenses, and they support employees in office jobs and managerial jobs to minimize employee expenses. Firm 05 stated that this method is not sustainable and can only be used during the crisis period.

Based on the findings of the study, it can be concluded that micro-sized architecture, engineering, and construction firms (MSAECFs) have a unique advantage due to their flexible and innovative structures, which enables them to survive in uncertain economic conditions. The survival strategies used by these firms include broadening stakeholder networks, strengthening relationships with suppliers/sub-contractors, diversifying into new markets, advertising through social media, web, and print publications to get new projects. These strategies are crucial for micro-sized companies to adapt to current market conditions and remain competitive. However, it should be noted that these strategies are not limited to MSAECFs only, and larger companies can also learn from them to build their resilience against economic fluctuations. Overall, the study highlights the importance of innovative and flexible structures for companies to survive in uncertain economic conditions, which is a valuable lesson for businesses across industries and sizes.

Conclusion

The article discusses the survival strategies of micro-sized architecture, engineering, and construction firms (MSAECFs) in Türkiye. The construction sector in Türkiye has been adversely affected by various factors such as regional wars, earthquakes, inflation, and exchange rate increases. The research shows that micro-sized companies are more innovative and flexible, which allows them to adapt to the current market conditions much more quickly than larger-scale companies. The article suggests that broadening stakeholder networks for new clients and projects, strengthening relationships with suppliers/sub-contractors, diversifying into new markets, advertising through social media, web, and print publications are some of the strategies used by micro-sized AEC companies to survive in uncertain economic conditions.

In conclusion, micro-scale architecture, engineering, and construction firms (MSAECFs) play a vital role in the Turkish construction sector, as they constitute a significant percentage of the total number of enterprises. The research findings suggest that MSAECFs have a unique advantage due to their flexible and innovative structures, which enables them to survive in uncertain economic conditions. These strategies are crucial for micro-sized companies to remain competitive and adapt to current market conditions. The study highlights the importance of innovative and flexible structures for companies to survive in uncertain economic conditions, which is a valuable lesson for businesses across industries and sizes.

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References

Adabre, M. A., Chan, A. P. C., Edwards, D. J., & Osei-Kyei, R. (2022). To Build Or Not To Build, That is The Uncertainty: Fuzzy Synthetic Evaluation of Risks for Sustainable Housing in Developing Economies. *Cities*, 125, 103644.

Arici Ustuner, Y., & Balaban Okten, B. (2022). Construction in Uncertain Economic Conditions. *7 th International Project and Construction Management Conference (IPCMC2022)*, Istanbul, Turkey.

Building an innovation strategy for SMEs: An analysis of the construction industry in Turkey. (2019). *Strategic Direction*, *35*(1), 30–32. https://doi.org/10.1108/SD-10-2018-0208/FULL/XML

Chih, Y. Y., Hsiao, C. Y. L., Zolghadr, A., & Naderpajouh, N. (2022). Resilience of Organizations in the Construction Industry in the Face of COVID-19 Disturbances: Dynamic Capabilities Perspective. *Journal of Management in Engineering*, *38*(2). https://doi.org/10.1061/(asce)me.1943-5479.0001014

Danforth, E. M., Weidman, J. E., Farnsworth, C. B., & Asce, M. (2017). *Strategies Employed and Lessons Learned by Commercial Construction Companies during Economic Recession and Recovery*. https://doi.org/10.1061/(ASCE)

Li, G., Zhang, G., Chen, C., &; Martek, I. (2020). Empirical Bid or No Bid Decision Process in International Construction Projects: Structural Equation Modelling Framework. *Journal of Construction Engineering and Management*, 146(6), 04020050.

Lim, B. T. H., Oo, B. L., & Ling, F. (2010). The Survival Strategies of Singapore Contractors in Prolonged Recession. *Engineering, Construction and Architectural Management*, 17(4), 387–403.

Okudan, O., Budayan, C., & Arayici, Y. (2022). Identification and Prioritization of Key Performance Indicators for the Construction Small and Medium Enterprises. *Teknik Dergi*, *33*(5), 12635–12662. https://doi.org/10.18400/TEKDERG.977849

Oviedo-Haito, R. J., Jiménez, J., Cardoso, F. F., & Pellicer, E. (2014). Survival Factors for Subcontractors in Economic Downturns. *Journal of Construction Engineering and Management*, *140*(3). https://doi.org/10.1061/(asce)co.1943-7862.0000811

Tansey, P., Meng, X., & Cleland, D. (2013). A Critical Review of Response Strategies Adopted by Construction Companies During An Economic Recession. *Proc., 29th Annual ARCOM Conf.*, S. D. Smith and D. D. Ahiaga-Dagbui, eds., Association of Researchers in Construction Management, Reading, U.K.

Tummalapudi, M., Killingsworth, J., & Harper, C. M. (2020). *Evaluation of Construction Surety Bonding Criterion for Changing Economic Conditions*.

Tummalapudi, M., Killingsworth, J., Harper, C., & Mehaney, M. (2021). US Construction Industry Managerial Strategies for Economic Recession and Recovery: A Delphi Study. *Journal of Construction Engineering and Management*, *147*(11). https://doi.org/10.1061/(asce)co.1943-7862.0002175

Ulubeyli, S., Kazaz, A., & Sahin, S. (2018). Survival of construction SMEs in macroeconomic crises: Innovation-based competitive strategies. *Journal of Engineering, Design and Technology*, *16*(4), 654–673. https://doi.org/10.1108/JEDT-03-2018-0057/FULL/PDF

Letter of Credit Usage in Liquefied Natural Gas Trade with Blockchain and Smart Contracts

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Abstract

Liquefied Natural Gas (LNG) trade is pivotal for economic development and clean energy. Its transportability over long distances allows countries to diversify their energy sources, reducing dependence on a single supplier. With its relatively cleaner combustion compared to other fossil fuels, LNG contributes to environmental sustainability, aiding the transition towards cleaner energy mixes. A Letter of Credit (LoC) plays a crucial role in LNG trade by serving as a financial instrument that mitigates risks and ensures smooth transactions between buyers and sellers. In the complex and high-value world of liquefied natural gas commerce, a LoC acts as a guarantee, assuring both parties of payment once predefined conditions are met. This is particularly vital in international trade, where parties may be unfamiliar with each other and where transactions involve substantial sums and intricate logistics. The LoC provides payment assurance, facilitates compliance with contractual agreements, and fosters trust by offering a standardized and globally recognized method of payment. However, LoC brings many problems with its application such as extra costs and slow processes. This paper investigates the use of blockchain and smart contracts as an innovative method for the use of LoC in LNG trade.

Keywords: *blockchain, LNG trade, Letter of Credit.*

Introduction

While global energy demand continues to rise, particularly in emerging economies, Liquified Natural Gas (LNG) provides a versatile and cleaner alternative to traditional fossil fuels like coal and oil. LNG emits fewer greenhouse gases and pollutants compared to coal and oil when burned, making it an attractive option for countries aiming to meet global climate actions. Moreover, it offers flexibility in terms of its usage, allowing it to be an energy source in various sectors such as power generation, transportation with LNG-fueled vehicles, and heavy industries. Recent years advances in LNG technology with liquefaction and transportability have made it more cost- effective and efficient and LNG market has witnessed a large trade volume with 124 .7 mt (Gao et al., 2024).

Together with increasing demand for LNG trade and developments in LNG technology, payment risks within international partners become an important issue due to volatility in international currencies, trust issues between traders and costs of payment methods. Payment risks are traditionally minimized with LoC in international trades. LoC has been a trusted way of international trades with buyer, seller and third parties however, due to bureaucracy involved in paper-based transactions and long processes involving different international partners, alternative payments methods are still being discussed (Uysal et al., 2022).

Recent advancements in blockchain technology offers various solutions to address the limitations associated with traditional LoC applications. Reducing the need for third-party involvement, allowing for automated contractual agreements and cost reduction, blockchain technology has many premises. Furthermore, the inherent features of blockchain, such as decentralization, transparency and immutability, could facilitate their wider adoption in international trades. The use of smart devices enables the possibility of physical control and delivery verification which reduces the cost of paper-based transactions.

This paper investigates usage of blockchain as an alternative method for LoC in international trades particularly for LNG industry. This paper is organized as follows: In section two, LoC and its applications in the LNG industry as a literature review will be discussed. A blockchain and smart contract-based framework is proposed in section three. Barriers on the implementation of blockchain as an alternative method to traditional LoC applications will be discussed in section four. Concluding remarks are made for a more effective payment process in LNG trade will be discussed and summarized in the final section.

Literature Review

Blockchain is commonly referred to as a component of distributed ledger technology. It functions as a record of transactions. Because of its high level of transparency, and decentralization blockchain is frequently characterized as 'trustless' (Zheng et al., 2017). It operates as a dependable, communal, and publicly accessible ledger that is open for verification by anyone, without any single entity having exclusive control over it.

The integration of blockchain technology into application in various industries has sparked significant research and implementation efforts worldwide. However, LNG industry has its own opportunities and limitations which has been explored with limited efforts. Sananes (2019) delvedinto the application of smart contracts in LNG trade, analyzing contract clauses aligned with British law implications. Reuters reported in 2018 the launch of the first blockchain-based commodity trading platform, Komgo SA, in Geneva, demonstrating a collaborative effort among global banks and trading firms. Ernst and Young (2017) highlighted the suitability of blockchain for energy and commodity trading, citing projects like a European energy consortium developing a blockchain platform for electricity and natural gas transactions. IBM has been a pivotal player in the adoption of blockchain technology across industries, with initiatives ranging from financial solutions to supply chain management. Collaborations with companies like Maersk have led to the development of blockchain-based transportation and supply chain systems. Furthermore, IBM's Transparent Supply Chain and Food Safety solutions showcase the potential for blockchain to enhance transparency and accountability in various sectors. Uysal et al. (2022) proposed a blockchain framework of LoC particularly designed for construction procurement processes in international trades. Advantages of this framework was focusing on reliability of the system and automated process.

Despite the promising potential of blockchain, concerns persist regarding their legal framework, privacy risks, and dependence on intermediaries. Studies from institutions like the University of Tartu (Eenmaa & Schmidt-Kessen, 2019) shed light on the trust dynamics in blockchain and their impact on market environments. Meanwhile, initiatives like the Open Trade Blockchain platform and PSA's collaboration with IBM signify ongoing efforts to leverage blockchain for trade document sharing and port management indicated a continued exploration of blockchain's role in facilitating international trade processes.

Al-Amaren et al. (2020) underlined the fact that shortage of laws on LoC usage limits its applicability. Legal evaluations, on blockchain and smart contracts applicability in letters of credit, and academic discussions, including University of Adelaide Law School's examination of smart contracts (Giancaspro, 2017), contribute to understanding the legal and regulatory landscape surrounding these technologies.

LoC in International LNG Trade

LoC, in its broadest sense, can be defined as the obligation of a bank to make payment to the seller, in line with the buyer's instructions, if certain conditions are met. LoC is a reliable payment method that ensures payment security between parties in international trade. The LoC transaction is considered a useful method in solving the problem of uncertainty in the conduct of international trade due to the simultaneous and mutual execution of transactions. LoC ensures the preservation of trust between the buyer and the seller because payment will not be made if the documents are not presented correctly and completely. Additionally, a LoC can make it easier for the seller to obtain loans from other banks and offer flexibility in providing financing. LoC has assurance, payment and credit functions. This transaction, carried out through banks, can serve as a kind of insurance against crises that may occur between the parties in international trade. For these reasons, LoC is a frequently preferred payment method in international trade.

To summarize the basic stages of the LoC process:

1st. Contract and Decision: In the basic sales contract between the buyer and the seller (importer and exporter), a decision is made that the payment will be made by LoC.

2nd. Opening a LoC: The importer (LoC supervisor) must inform the issuing bank in the LoC opening instruction about all the details regarding this LoC, such as the LoC maturity, loading period, transportation route, invoice, loading document, insurance document, etc., and how the documents representing the goods will be prepared.

3rd. Correspondent Bank (Seller's Bank): The bank determined by the buyer opens the LoC to the beneficiary bank and notifies the bank. The importer's bank transmits the LoC to the correspondent bank in the exporter's country.

4th. Document Submission: The seller fulfills the conditions specified in the LoC and submits the documents representing the goods to the correspondent bank in accordance with the contract. The conformity of the documents must comply with the terms in the LoC.

5th. Document Review: The correspondent bank examines the submitted documents and checks compliance with the conditions in the LoC. Sends the documents to the issuing bank. The issuing bank also examines the documents according to the terms of the LoC.

6th. Payment: If the documents submitted comply with the conditions in the LoC, payment is made and reaches the seller.

7th. Closing of the LoC: When the transaction is completed, the LoC is closed.

Advantages and Disadvantages of LoC

LoC has many practical advantages. Firstly, it provides trust between the international parties. It is a reliable payment method for the seller as the buyer receives a bank commitment that payment will be made to the seller by meeting certain conditions. Practically speaking, within international partners building reliability in terms of payment can be settled with LoC only. Secondly, it also solves the problem of uncertainty in the order. While the seller knows that he will receive payment when he submits certain documents, the buyer reduces the risk of paying before the goods are delivered. Thirdly, it is widely used in international trade. Therefore, many commercial companies accept and use this payment method. Fourthly, from political and economic risks based on transactions it minimized the payment risks since it is carried out through banks. Lastly sellers may have the possibility of obtaining loans from banks by using letters of credit, making it easier to obtain financial resources.

Despite its high practical advantages, LoC has disadvantages which hinders its acceptance. Firstly, transactions can be costly due to bank commissions, review fees and other expenses. This can increase the costs of trading. Secondly, transactions can sometimes be bureaucratic. Accurate and complete preparation and review of documents takes more time than expected. Thirdly, it is subject to certain conditions and it may be difficult to operate outside of these conditions which makes ita tailored to fit solution to each case. Disagreements between the parties or changing circumstances may complicate the execution of the LoC. Fourthly, payment depends on the correct presentation of documents only. Payment may be delayed or rejected if there are errors or omissions in the documentation. Traditional LoC transactions generally relies on paper documents and may require physical documents to be transmitted to banks. That being said, finally, all process takes a long time due to the physical examination of documents and correspondence between banks.

Proposed Blockchain Based Framework

In this paper a consortium blockchain network is proposed for the blockchain-based LoC model. This network is open to members only and only certain participants in the network are authorized to make transactions. Other members of the network can only monitor transactions if they are allowed to do so. Therefore, consortium blockchain networks do not experience the privacy problems as in public blockchain networks. Considering these features, it is concluded that consortium blockchain networks are an ideal for LoC to ensure cooperation between actors operating in the same industry.

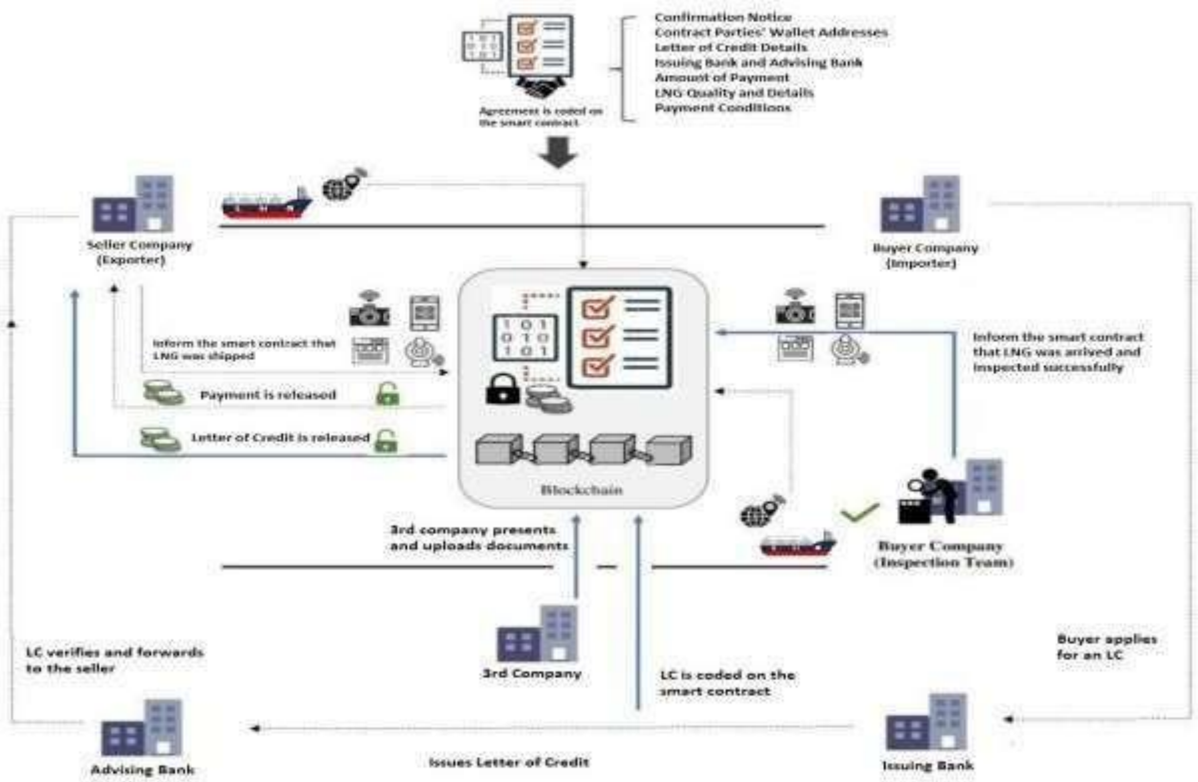

Figure 1: Proposed framework.

In a sector-based consortium blockchain network, the correspondent bank can be a voluntarily member. The bank, which issues the LoC and uploads it to the blockchain, can quickly transmit the information that the LoC has been opened to the correspondent bank via the blockchain. Hence, the LoC is made available to the correspondent bank almost instantly. The correspondent bank that receives this notification adds the beneficiary as a participant in the network. The legal relationship between the issuing bank and the beneficiary arises from this notification. In addition, the issuing bank may include persons other than the parties responsible for issuing the documents specified in the terms of the LoC into the blockchain and grant permission to upload documents directly to these persons. In the traditional LoC process, the information that the LoC was opened was notified to the correspondent bank by the issuing bank using letters and telecommunication methods (telegram, telex, fax, SWIFT, etc.). However, in a blockchain based LoC contract, all notifications are made via the blockchain. The proposed blockchain based framework is summarized in Figure1.

In a blockchain-based LoC, the smart contract created by the issuing bank must be signed with the private key of the issuing bank and send the necessary information to the public key of the correspondent bank. The time when the data was sent can be determined by the time stamp in the blocks. By connecting the block containing the smart contract to the chain, the correspondent bank can conclude that the smart contract has been executed.

With the use of blockchain and smart contracts in the LoC process, tracking and sharing of data becomes more secure and efficient. The distributed structure of the blockchain, enables the process to be operated more securely and effectively for the parties involved in the transaction. This new approach saves cost and time by reducing the need for third parties. Tracking documents via blockchain reduces the cost and time loss caused by document exchange. Blockchain protects the integrity of data, which increases the security of the information contained in documents. In the traditional LoC process, there is a risk of documents being lost during circulation among many banks. This risk can be overcome because data cannot be changed after being added to the blockchain. The traceability of the blockchain supports the independence of the LoC and banks' reliance on documentation. In this way, the risk assumed by the issuing bank is reduced in case the beneficiary uses a statement that appears to comply with the terms of the LoC but is contrary to the underlying contract.

The implementation of blockchain-based letters of credit may also present some difficulties. Documents need to be exchanged electronically and countries' domestic laws need to adapt to paperless trade. Additionally, the legal validity of blockchain-based letters of credit and their status before the judiciary should also be evaluated. Blockchain technology can increase efficiency in LoC transactions, make the process more secure and reduce costs. However, issues such as the integration of this technology with LoC processes, the legal validity of the process and compliance with the law need to be carefully addressed.

Conclusion

Blockchain includes a distributed database consisting of blocks linked together by cryptographic methods. The smart contracts can be included in the blockchain to allow mutual agreements to occur digitally. It is possible to establish a LoC relationship on a digital platform using blockchain and other relevant technologies via smart contracts. Since the identity of the parties performing transactions in the blockchain is verified with public and private keys, a reliable connection can be established between the parties through the blockchain. Therefore, it is concluded that blockchain-based smart LoC contracts can be implemented in the LNG trade where both buyers and sellers have international identities.

In this paper a consortium blockchain network is proposed for the blockchain-based LoC model to ensure privacy. The consortium blockchains however, are partially decentralized an rely on consortium members for execution of smart contracts. A hybrid blockchain which consists of a combination of public blockchain (e.g., Ethereum) and a consortium blockchain for LoC could be a future study area to achieve privacy and decentralization at the same time.

References

Al-Amaren, E. M., Ismail, C. T. B. M., & Nor, M. Z. B. M. (2020). The blockchain revolution: A gamechanging in LoC (L/C). *International Journal of Advanced Science and Technology, 29*(3), 6052- 6058.

Eenmaa-Dimitrieva, H., & Schmidt-Kessen, M. J. (2019). Creating markets in no-trust environments: The law and economics of smart contracts. *Computer Law & Security Review*, *35*(1), 69-88.

Gao, S., Zhang, G., Guan, C., Mao, H., Zhang, B., & Liu, H. (2023). The expansion of global LNG trade and its implications for CH4 emissions mitigation. *Environmental Research Letters*, *19*(1), 014022.

Giancaspro, M. (2017). Is a 'smart contract'really a smart idea? Insights from a legal perspective. *Computer Law & Security Review*, *33*(6), 825-835.

Larson D. (2018). Mitigating risky business: Modernizing letters of credit with blockchain, smart contracts, and the internet of things. *Mich. St. L. Rev.*, *929*, 930-983.

Sananes, G. (2019), *Implementation of smart contract in the liquefied natural gas trade*. [Published Thesis, Haute école de gestion de Genève (HEG-GE) International Business Management].

Uysal, F., Ahmadisheykhsarmast, S., & Sonmez, R. (2022). A smart contract framework as an alternative method for letter of credit use in construction procurement. In *The Twelfth International Conference on Construction in the 21st Century (CITC-12)* (pp. 643-649).

Zheng, Z., Xie, S., Dai, H., Chen, X., & Wang, H. (2017). An overview of blockchain technology: Architecture, consensus, and future trends. In *2017 IEEE international congress on big data (BigData congress)* (pp. 557-564).

Defining Critical Criteria for Successful Implementation of Distance Architectural Education

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Abstract

The far-reaching impact of the COVID-19 pandemic in Turkey led to varied measures across sectors to mitigate its effects. Among these measures, the rapid adoption of distance learning emerged as a crucial response, especially within the educational environment. However, this shift faced challenges, notably in architecture departments due to their emphasis on practical course. Identifying the critical success criteria (CSCs) for distance architectural education (DAE) is vital to make the distance education system more suitable for architectural education (AE). Therefore, this study aimed to highlight the CSCs for DAE. Through a systematic literature review (SLR) of 465 articles, 67 success criteria (SCs) were identified under six categories; technical and technological infrastructure (11 items), health and psychology (12 items), pedagogy (9 items), interaction, satisfaction, and communication (10 items), educational adaptation (22 items), and economic factors (3 items). The questionnaire, designed by 67 SCs, used a 5-point Likert scale as a measuring instrument. It was administered to architecture students who had completed all their courses for at least one semester through distance education systems in Turkey. A total of 232 valid questionnaires were collected and meticulously analyzed using both reliability analysis and normalized mean values (NMVs). NMVs were calculated for each group individually to identify category-specific CSCs. Among the 67 SCs examined, this study identified 37 as CSCs for the successful implementation of DAE in Turkey.

Keywords: *architectural education, COVID-19, distance education, online learning, success factors.*

Introduction

Architectural Education (AE) is the initial stage where fundamental professional training is provided, laying the foundations for the commencement of professional practice. Primarily characterized by experiential learning, AE distinguishes itself from other methods through its emphasis on skill acquisition (Demirbas & Demirkan, 2007; Schön, 1992). It involves a series of engagements that foster a dynamic exchange between the instructor and the student, facilitating visual and auditory communication to enhance the learning process (Ceylan et al., 2021). In this process, the instructor demonstrates through drawing and practical engagement, while the student observes and listens, interpreting the conveyed information to develop their own proposals. This cycle persists, evolving through the instructor's critique of the student's suggestions. Schön (1992) refers to this feedback loop as "*reflective practice*." This dynamic involvement and co-creation between student and instructor are active learning, as supported by scholars (Alnusairat et al., 2021; Ceylan et al., 2021).

The distinctive structure of AE shows the need for a learning environment prioritizing face-to-face, hands-on learning, and collaborative engagement among students within studio settings, crucial for an effective educational process. However, the unforeseen outbreak of the COVID-19 pandemic in 2020 rendered this unfeasible.

The global suspension of face-to-face education across all levels, prompted by the COVID-19 pandemic, necessitated urgent measures to ensure educational continuity. Consequently, architecture departments swiftly shifted to online education, aligning with the technical and technological capabilities of their respective affiliated universities, in response to this unforeseen circumstance. Despite its mismatch with the nature of AE, the prolonged adoption of the distance education model became necessary to mitigate contagion risks, replacing active learning with passive methods (Ceylan et al., 2021). However, this adaptation is deemed unsuitable for the unique structure of AE highlighted earlier. Essentially, without the use of appropriate methods and approaches, the distance education system predominantly features passive learning, where information is solely transmitted from the instructor to the student (Megahed & Hassan, 2022).

In fact, the inherent contrast between distance education and AE has resulted in several challenges within architectural higher education, encompassing limited peer interaction (Megahed & Hassan, 2022), privacy concerns (Ibrahim et al., 2021), feelings of alienation (George, 2018), restricted access to resources (Bakir & Alsaadani, 2022), a lack of support (Al Maani et al., 2021), and issues related to poor internet connectivity (Varma & Jafri, 2021). Additionally, this shift eliminated face-to-face core courses that provided students with firsthand experiences of buildings, consequently restricting their ability to feel materials, move through spaces, and engage in interactions with instructors (Travis, 2022).

Therefore, assessing how the distance education system impacts students, who serve as focal points in implementing distance education in architecture schools, becomes crucial for the future of AE. Additionally, developing effective and efficient strategies aligned with the unique characteristics of AE becomes imperative for optimizing the distance education system. In this regard, navigating the aforementioned challenges and ensuring the continuity of the AE process hinges upon identifying the criteria that cause these issues and influence the success of distance architectural education (DAE). Hence, the aim of this research is to identify the critical criteria that influence the successful implementation of DAE.

Research Methodology

To identify and emphasize the critical success criteria (CSCs) for the successful implementation of DAE in Turkey, a mixed research design was employed, starting with a qualitative method and transitioning to quantitative. Following a four-stage methodological framework, potential success criteria (SCs) were identified through systematic literature review (SLR).

Subsequently, a questionnaire was designed, administered, and followed by data collection. Statistical analyses were then conducted to achieve the study's objectives.

Determining SCs Affecting the Successful Implementation of DAE

The initial stage of the current study involved identifying the SCs that influence the successful implementation of DAE. Therefore, an extensive review of existing literature through a SLR. In this context, the Web of Science (WoS) database was utilized to access scientific papers. The search parameters in WoS were set using specific keywords in the search query: (ALL FIELDS) "*architectural education*" AND "*distance education*" AND "*COVID-19*". In this first search, 465 publications were identified.

To select relevant studies, well-defined exclusion and inclusion criteria were rigorously applied. Initially, exclusion criteria such as language, categories, and publication type were used, resulting in the elimination of 79 records. Subsequently, inclusion criteria were employed, focusing on aspects such as relevance to the COVID-19 pandemic and architectural education, simultaneous addressing of identified keywords, alignment with research objectives, full-text accessibility, and relevance to existing literature. This stringent filtering process led to the exclusion of 342 studies. Following a thorough review for relevance, 44 articles remained, forming the foundation for developing a questionnaire.

Through a detailed analysis, 67 success criteria (SCs) influencing the success of DAE were identified. These SCs exhibited similarities and were investigated based on their scope and impact areas. The aim was to identify latent influential factors by expanding the criteria's dimensions. Subsequently, the obtained criteria were further analysed and organized into sub-dimensions, considering their content and emphasized features. These were then categorized/grouped into themes and labelled according to the characteristics highlighted by the criteria they encompass: "technical and technological infrastructure," "health and psychology," "pedagogy," "interaction, satisfaction, and communication," "educational adaptation," and "economic factors." It is acknowledged that the criteria within these themes intersect, forming a cohesive framework. This categorization was based on their impact, scope, and focus, aiming to provide a comprehensive understanding of the factors at play. The definition of factors and categorization of SCs took into account their respective impact areas.

Organizing and Administrating the Questionnaire

Subsequent to the SLR, a survey was developed and administered among architecture students in Turkey. This survey was meticulously designed to evaluate the SCs influencing the successful implementation of DAE.

Comprising two sections covering SCs and demographic variables, the survey includes 67 SCs categorized as follows: 11 for *Technical and Technological Infrastructure*, 12 for *Health and Psychology*, 9 for *Pedagogy*, 10 for *Interaction, Satisfaction, and Communication*, 22 for *Educational Adaptation*, and 3 for *Economic Factors*, Participants rated a five-point Likert-type scale, ranging from "1" (*None*) to "5" (*Very Highly*), to assess the significance of these SCs, considering their experiences and expectations in DAE.

The sample group consisted of architecture students studying in Turkey and completed at least one semester of their courses through DAE. Questionnaires were distributed via email to 2258 architecture students. Data were collected from April 30th to June 28th, 2022. A total of 232 completed questionnaires were received and used as material for this research, representing a response rate of 10.27%.

Data Analysis

The data were analyzed using Statistical Package for Social Sciences (SPSS) 26.0 software, involving various statistical tests such as reliability analysis and normalized mean values (NMVs).

To assess the internal consistency of Likert scale-based survey questions, measuring reliability is crucial (Nunnally & Bernstein, 2007). Therefore, Cronbach's alpha (α) coefficient was utilized to determine the statistical reliability and validity of participants' responses. The "α" coefficient values span from 0 to 1, with a set minimum acceptable reliability benchmark of 0.7 (Cronbach, 1951; Tavakol & Dennick, 2011).

To achieve the main objective of this research, determining the ranking of SCs was crucial and was accomplished through MNV analysis. This analysis specifically involved utilizing NMVs to assess the criticality of the 67 SCs that influence the successful implementation of DAE. NMVs for each SC were calculated using Equation 1.

$$Normalised\ mean\ value = \frac{(mean\ of\ SC - lowest\ mean)}{(highest\ mean - lowest\ mean)} \quad (1)$$

To select the CSCs, mean values were normalized, with dataset groups standardized to the "0-1" interval to identify the most critical ones. This methodology follows the approach by Xu et al. (2010), who identified factors with normalized values equal to or greater than 0.5 as critical. The decisive factor here is that the normalized value should approach 1, indicating increasing criticality. Below 0.5 is not defined as critical, as going below this threshold would move away from the maximum value. Therefore, any success criteria with a NMV equal to or greater than 0.5 are considered critical. This principle aligns with previous studies by Liao & Teo (2017), Zhou et al. (2019), and Zhao et al. (2014, 2015).

Findings

As an initial step, the questionnaire's internal consistency and reliability were assessed using Cronbach's alpha (α) coefficient. The dataset's α coefficient for the 67 SCs impacting the successful implementation of DAE was calculated to be 0.985, exceeding the minimum threshold of 0.7 (Tavakol & Dennick, 2011).

Subsequently, individual NMV analyses were conducted for each group to pinpoint the specific CSCs within each category. Upon analysis, it was determined that out of the 67 SCs, 38 met the criteria for being CSCs. These include 6 related to Technical and *Technological Infrastructure*, 10 to *Health and Psychology*, 4 to *Pedagogy*, 4 to *Interaction, Satisfaction, and Communication*, 12 to *Educational Adaptation*, and 2 to *Economic Factors*. These identified CSCs significantly impact the successful implementation of DAE in Turkey.

Regarding the *Technical and Technological Infrastructure* CSCs, the means, NMVs, and standard deviations (SD) of SCs within this category were computed based on the questionnaire responses (Table 1).

Table 1. Ranking of SCs related to Technical and Technological Infrastructure.

Factors	Code of SCs	Success Criteria (SCs)	Mean	SD	NMV	Ranking
Technical and Technological Infrastructure	T1	Lack of an adequate technical background to solve networking and software related issues	3.10	1.318	0.318	10
	T2	Technical issues	3.23	1.308	**0.500***	6
	T3	Lack of fast and stable internet connection	3.42	1.400	**0.672***	3
	T4	Opportunity to access recorded lectures and juries at any time	3.69	1.417	**0.918***	2
	T5	Low-screen resolution quality - The screen resolution makes it difficult to see the design work in detail	3.19	1.438	0.463	7
	T6	Flexibility to run the applications on a variety of devices (e.g. mobile devices, tablets, and laptops)	3.78	1.252	**1.000***	1
	T7	The emergence of cyber security risks	2.68	1.260	0.000	11
	T8	Insufficient screen resolution to accurately display and critique scaled drawings	3.08	1.387	0.363	9
	T9	Lack of the possibility of drawing or sketching on the screen; difficulties with using the mouse for sketching	3.33	1.401	**0.590***	4
	T10	Issues with the availability of up-to-date and appropriate hardware and software platforms	3.09	1.383	0.372	8
	T11	The need for user-friendly interfaces and applications to make e-learning easy	3.25	1.311	**0.518***	5

***** Indicates the item is a CSC (normalization value ≥ 0.50), NMV: Normalised Mean Value, SD: Standard Deviation.

SCs with NMVs not less than 0.50 are identified as CSCs. Among the 11 SCs in this category, six have normalized values exceeding 0.50, categorizing them as CSCs. Particularly, "*Flexibility to run the applications on a variety of devices (e.g. mobile devices, tablets, and laptops)*" (T6) emerged as the most CSC for Technical and Technological Infrastructure.

The means, NMVs, and SD of the SCs related to *Health and Psychology* were computed based on the questionnaire responses and are presented in Table 2.

Table 2. Ranking of SCs related to Health and Psychology.

Factors	Code of SCs	Success Criteria (SCs)	Mean	SD	NMV	Ranking
Health and Psychology	HP1	Lack of guidance and support	3.26	1.396	**0.769***	2
	HP2	Lack of privacy (felt by both teachers and students)	2.76	1.283	0.000	12
	HP3	Time and workload management (i.e. an increase in the number of tasks	3.03	1.414	0.415	11
	HP4	Increased sense of isolation, and disconnection from peers and colleagues	3.17	1.410	**0.630***	5

	HP5	Psychological problems/negative feelings that could lead to alienation, uncertainty, confusion, and identity loss	3.10	1.415	**0.523***	10
	HP6	The dissolved boundaries between the work environment and home environment (i.e. struggle with establishing boundaries between work and family)	3.12	1.409	**0.553***	8
	HP7	When feedback is delayed, students feel stress, frustration, and confusion	3.41	1.392	**1.000***	1
	HP8	The lack of emotional connection	3.15	1.405	**0.600***	7
	HP9	Insufficiency of self-discipline and concentration issues	3.16	1.369	**0.615***	6
	HP10	Extended working hours for instructors	3.24	1.414	**0.738***	4
	HP11	Instructors are struggling to keep students concentrated throughout the lesson	3.24	1.352	**0.738***	3
	HP12	Instructors are struggling to motivate students to ask question	3.11	1.323	**0.538***	9

***** Indicates the item is a CSC (normalization value ≥ 0.50), NMV: Normalised Mean Value, SD: Standard Deviation.

The results indicated that, out of the 12 SCs in this category, ten have normalized values exceeding 0.50, classifying them as CSCs. Specifically, "*When feedback is delayed, students feel stress, frustration, and confusion*" (HP7) emerged as the most CSC for Health and Psychology.

The means, NMV, and SD of SCs related to the *Pedagogy* were computed based on questionnaire responses to identify the CSCs (Table 3).

Table 3. Ranking of SCs related to Pedagogy.

Factors	**Code of SCs**	**Success Criteria (SCs)**	**Mean**	**SD**	**NMV**	**Ranking**
Pedagogy	P1	Online learning enables students to customize their experience based on their learning style	3.22	1.265	0.344	6
	P2	Enabling students to discover their potential and develop their abilities	3.09	1.266	0.120	8
	P3	Due to the inability to create campus-culture and university spirit online, students are deprived of this opportunity	3.46	1.444	**0.758***	4
	P4	It helps students to realize their ability to be productive under sudden changing conditions	3.02	1.294	0.000	9
	P5	Without facial expressions and body language, designs and presentations become rather dull for participants	3.27	1.374	0.431	5
	P6	Expectation from students to be more responsible for their own education	3.17	1.277	0.258	7
	P7	Opportunity to improve computer skills	3.48	1.252	**0.793***	3
	P8	Lack of skills to utilize devices or facilities (the need for more time and practice to use new software and applications)	3.56	1.298	**0.931***	2
	P9	Instructors' inability to integrate technology or insufficient software skills (which influences the efficiency of the course)	3.60	1.302	**1.000***	1

***** Indicates the item is a CSC (normalization value ≥ 0.50), NMV: Normalised Mean Value, SD: Standard Deviation.

The results showed that four criteria among the 9 SCs in this group have normalized values greater than or equal to 0.50, thus classifying them as CSCs. "*Instructors' inability to integrate technology or insufficient software skills (which influences the efficiency of the course)*" (P9) is determined as the most CSC for Pedagogy.

To analyze the CSCs related to *Interaction, Satisfaction, and Communication*, the means, NMV, and SD of SCs within this category were derived from the questionnaire responses (Table 4).

Table 4. Ranking of SCs related to Interaction, Satisfaction, and Communication.

Factors	Code of SCs	Success Criteria (SCs)	Mean	SD	NMV	Ranking
Interaction, Satisfaction, and Communication	ISC1	Students are struggling to understand online lectures, design juries, and critiques	3.22	1.310	0.296	5
	ISC2	Lack of peer learning	3.32	1.412	0.481	9
	ISC3	Students are uncomfortable because they cannot view their classmates' progress and projects	3.06	1.393	0.000	10
	ISC4	Lack of interaction, communication, and cooperation among students	3.37	1.365	**0.574***	4
	ISC5	Low interaction and communication issues among students and between and students and instructors	3.30	1.372	0.444	8
	ISC6	The potential of collaborating with institutions and professionals all around the world	3.43	1.294	**0.685***	3
	ISC7	Removal of geographic barriers	3.60	1.248	**1.000***	1
	ISC8	The difficulties in understanding teachers' instructions online	3.25	1.314	0.351	6
	ISC9	It increases cooperation and interaction between universities and students on a national and international level	3.28	1.307	0.407	7
	ISC10	Students' previous familiarity with the tutors has positive effects on lessons, projects, and assignments	3.47	1.289	**0.759***	2
***** Indicates the item is a CSC (normalization value ≥ 0.50), NMV: Normalised Mean Value, SD: Standard Deviation.						

The findings revealed that, among the 10 SCs in this group, four displayed normalized values surpassing 0.50, categorizing them as CSCs. Particularly, "*Removal of geographic barriers*" (ISC7) emerged as the most CSC for Interaction, Satisfaction, and Communication.

In relation to the CSCs under *Educational Adaptation*, the means, NMVs, and SD of the SCs within this category were obtained from the questionnaire responses (Table 5).

Table 5. Ranking of SCs related to Educational Adaptation.

Factors	Code of SCs	Success Criteria (SCs)	Mean	SD	NMV	Ranking
Educational Adaptation	EA1	It provides convenience for students to deliver course outputs (homework, etc.) to instructors	3.55	1.295	**1.000***	1

	EA2	Working with 3D models and animations without hand sketches or physical models makes expressing design ideas difficult	2.99	1.366	0.243	18
	EA3	Inadequacy of critique frequency and quantity	3.19	1.354	**0.513***	10
	EA4	Student assessment issues	3.08	1.325	0.364	13
	EA5	Lack of immediate access to teachers' help	3.29	1.338	**0.648***	6
	EA6	Concerns about cheating	3.19	1.397	**0.513***	12
	EA7	Providing flexibility	3.44	1.350	**0.851***	3
	EA8	Increased time spent on lectures and design critiques	3.25	1.344	**0.594***	7
	EA9	Students are dissatisfied with the new assessment criteria adapted to distance education	2.86	1.248	0.067	20
	EA10	It allows students considerable flexibility in arranging and attending tutorials	3.31	1.262	**0.675***	4
	EA11	Adequate and reliable assessment tools are needed due to unsupervised exams, projects, and assignments	3.24	1.326	**0.581***	9
	EA12	It allows students to take as many courses as they like within the curriculum	3.44	1.341	**0.851***	2
	EA13	It causes stereotypical designs that are far from aesthetic	3.03	1.361	0.297	16
	EA14	There will be a biased evaluation as the students' names are visible to the evaluators on screen while evaluating	2.81	1.340	0.000	22
	EA15	The focus on learning the technology rather than on the information taught	2.84	1.358	0.040	21
	EA16	Ability to allow an unlimited number of participants to participate in courses	3.31	1.345	**0.675***	5
	EA17	Unfamiliarity with quiz/exam formats	2.97	1.314	0.212	19
	EA18	Instructors are not able to know whether the lesson topics and contents are understood by the students	3.25	1.366	**0.594***	8
	EA19	Instructors cannot agree among themselves on student work or reconciling grades	3.04	1.282	0.310	15
	EA20	Instructors are having difficulty preparing, publishing, and administering online exams	3.01	1.289	0.270	17
	EA21	Having students' cameras turned on during online lecture sessions will greatly benefit their learning experience	3.06	1.281	0.337	14
	EA22	Working with drawings and 3D models in a digital environment without an adequate hand sketch prevents the designs from reaching the expected maturity level	3.19	1.376	**0.513***	11

***** Indicates the item is a CSC (normalization value ≥ 0.50), NMV: Normalised Mean Value, SD: Standard Deviation.

The results unveiled that among the 22 SCs in this category, twelve demonstrated normalized values exceeding 0.50, classifying them as CSCs. Specifically, "*It provides convenience for students to deliver course outputs (homework, etc.) to instructors*" (EA1) emerged as the most CSC for Educational Adaptation.

The means, NMV, and SD of SCs related to the *Economic Factors* were computed based on questionnaire responses to identify the CSCs (Table 6).

Table 6. Ranking of SCs related to Economic Factors.

Factors	Code of SCs	Success Criteria (SCs)	Mean	SD	NMV	Ranking
Economic Factors	EF1	Lack of access to resources	3.20	1.335	0.000	3
	EF2	A decrease in both the expenses for printing and its impact on the environment	3.66	1.399	**0.851***	2
	EF3	The absolute need for accessibility to hardware such as tablets and computers	3.74	1.346	**1.000***	1

***** Indicates the item is a CSC (normalization value ≥ 0.50), NMV: Normalised Mean Value, SD: Standard Deviation.

The analysis revealed that, out of the 3 SCs in this category, two have normalized values exceeding 0.50, classifying them as CSCs. Specifically, "*The absolute need for accessibility to hardware such as tablets and computers*" (EF3) emerged as the most CSC for Economic Factors.

Conclusion

The present study unveils the CSCs influencing the successful implementation of DAE in Turkey. This assessment is based on data collected from the different architecture departments nationwide.

According to the current study's findings; "*Flexibility to run the applications on a variety of devices (e.g. mobile devices, tablets, and laptops)*" emerged as the most critical among the eleven success criteria in the Technical and Technological Infrastructure category. Undoubtedly, the ability to access educational content across multiple devices is indeed a crucial technological convenience provided by distance education systems. Moreover, the widespread availability of these technologies significantly augments online learning. These technologies facilitate ubiquitous course tracking, provide flexibility for participants, and enable personalized education, enhancing the successful adoption of DAE.

Identified as the most critical among the twelve success criteria in the Health and Psychology category is the factor of "*When feedback is delayed, students feel stress, frustration, and confusion.*" Delay in feedback from instructors as a significant obstacle hampering the success of distance education systems in AE.

Ranked as the most critical among the nine success criteria in the Pedagogy category is the "*Instructors' inability to integrate technology or insufficient software skills (which influences the efficiency of the course).*" Enhancing instructors' skills in integrating technologies into teaching and learning inevitably leads to a more effective online learning environment. Therefore, instructors who grasp students' cognitive levels, tailor explanations and examples accordingly, and adeptly employ diverse teaching strategies in digital settings convey information more effectively. In this context, prioritizing instructors' technological ability and their comprehension of technology utilization is imperative for elevating the quality of DAE.

"*Removal of geographic barriers*" is determined as the most critical success criteria for Interaction, Satisfaction, and Communication, in this group among ten criteria. The flexibility of distance education, particularly concerning location and distance, is highly valued by architecture students. By sharing their work through digital documents, students transcend the physical confines of a design studio, fostering quicker and more fluid thinking, enabling rapid production of multiple designs. This adaptability also allows students to actively engage in various professional spheres.

Determined as the most critical among the twenty-two success criteria in the Educational Adaptation category is the factor of "*It provides convenience for students to deliver course outputs (homework, etc.) to instructors.*" DAE serves as a valuable method for developing technology-mediated educational materials and offers added flexibility to faculty and students in delivering course outputs and content. This technological advancement allows for instantaneous updating and sharing of materials and online resources. Additionally, using digitized resources and materials minimizes additional costs, subsequently reducing output and course expenses for architecture students involved in DAE.

Revealed as the most critical among the three success criteria in the Economic Factors category is the "*The absolute need for accessibility to hardware such as tablets and computers.*" Having a suitable device stands as one of the primary requirements for effective DAE. However, many architecture students encounter financial barriers, preventing them from accessing computers and similar devices essential for online learning. This lack of necessary equipment and funding serves as a significant obstacle to the adoption of DAE.

These results underscore the diverse range of critical success criteria across different dimensions essential for the successful implementation of DAE within Turkish higher education. In light of these findings;

- To ensure the success of distance education systems in AE, there should be a priority on technology-driven education. Increasing accessibility to mobile devices and broadening the use of alternative devices is crucial. Providing technical support and guidance to both students and instructors in utilizing DAE tools effectively would also be highly beneficial.

- Instructors should aim to shorten their response times to students. Increasing the frequency of feedback, as well as facilitating access to instructor assistance, is important. Offering direct access opportunities, especially during times of crisis, would significantly benefit students. Implementing cameras during courses can enhance online interaction and foster emotional connections. Encouraging students to ask questions and seek help when necessary is crucial. Establishing a feedback loop between instructors and students covering diverse topics can facilitate ongoing evaluations and improvements, fostering continuous cycles of development.

- Offering technology training for instructors involved in DAE will be beneficial. It's crucial to allow both students and instructors adequate time to familiarize themselves with new software and applications. Encouraging them to actively gain experience will further support their adaptation to these tools.

- Providing access to licensed software, platforms, and hardware like tablets and computers will be beneficial for DAE. Online access to resources such as libraries and archives greatly assists students. Leveraging digital opportunities to reduce course costs and favoring digital copies in selecting resources and materials prove advantageous.

- Ensuring students have suitable study environments is crucial. Implementing measures to prevent interruptions during class sessions is important for their focus. Additionally, raising awareness among family members about the importance of uninterrupted study time would be beneficial.

Future Directions

In this study, the most critical success criteria have been identified, and solutions proposed. However, from a broader perspective, several important recommendations can be developed to guide future research.

First, the COVID-19 pandemic has prompted a reassessment of educational methods in AE. However, the transition to online platforms is complex due to the unique nature of design courses. Therefore, innovative approaches are crucial.

Architectural schools should adapt to the post-pandemic landscape by rethinking curricula, resources, and flexibility. Taking a broader view, learning formats and design studios should be adaptable to online environments, particularly in aspects such as project-based learning, collaborative work, and critique sessions. Embracing educational technology can enhance collaborative learning, while understanding students' experiences can improve content delivery. Future developments in architectural pedagogy should integrate online teaching as a component for personalized learning. Investments in tailored approaches and educational technologies are necessary to accommodate diverse student needs. These insights are relevant beyond the pandemic, guiding educators in establishing robust distance education systems as the new normal in AE.

Apart from the negative impacts, the pandemic has opened up opportunities and novel pathways for enhancing educational pedagogy. Therefore, the findings of this study also hold relevance for the period beyond the pandemic; they could offer valuable insights to architectural educators aiming to shift from a temporary pandemic-induced setup to a durable, resilient framework for distance learning. Consequently, this transition could establish distance learning as the prevailing mode of education and assist educators in fulfilling the logistical objectives of academic institutions.

References

Al Maani, D., Alnusairat, S., & Al-Jokhadar, A. (2021). Transforming learning for architecture: online design studio as the new norm for crises adaptation under COVID-19. *Open House International*, *46*(3), 348-358.

Alnusairat, S., Al Maani, D., & Al-Jokhadar, A. (2021). Architecture students' satisfaction with and perceptions of online design studios during COVID-19 lockdown: the case of Jordan universities. *Archnet-IJAR*, *15*(1), 219-236.

Asadpour, A. (2021). Student challenges in online architectural design courses in Iran during the COVID-19 pandemic. *E-Learning and Digital Media*, *18*(6), 511-529.

Bakir, R., & Alsaadani, S. (2022). A mixed methods study of architectural education during the initial COVID-19 lockdown: student experiences in design studio and technology courses. *Open House International*, *47*(2), 338-360.

Ceylan, S., Şahin, P., Seçmen, S., Somer, M. E., & Süher, K. H. (2021). An evaluation of online architectural design studios during COVID-19 outbreak. *Archnet-IJAR*, *15*(1), 203-218.

Cronbach, L. J. (1951). Coefficient alpha and the internal structure of tests. *Psychometrika*, *16*(3), 297-334.

Demirbas, O. O., & Demirkan, H. (2007). Learning styles of design students and the relationship of academic performance and gender in design education. *Learning and Instruction*, *17*(3), 345-359.

George, B. H. (2018). Drawing online: a comparative analysis of an online basic graphics course. *Landscape Journal*, *37*(1), 23-37.

Ibrahim, A. F., Attia, A. S., Bataineh, A. M., & Ali, H. H. (2021). Evaluation of the online teaching of architectural design and basic design courses case study: College of Architecture at JUST, Jordan. *Ain Shams Engineering Journal*, *12*(2), 2345-2353.

Khan, A. R., & Thilagam, N. L. (2021). The confluence approach – a theoretical proposition for effective structuring of architecture studio pedagogy in e-learning mode. *Open House International*, *46*(4), 510-527.

Khan, A. R., & Thilagam, N. L. (2022). The virtual design studio and the key integrals. *Open House International*, *47*(2), 316-337.

Liao, L., & Teo, E. A. L. (2017). Critical success factors for enhancing the building information modelling implementation in building projects in Singapore. *Journal of Civil Engineering and Management*, *23*(8), 102-1044.

Megahed, N., & Hassan, A. (2022). A blended learning strategy: reimagining the post-Covid-19 architectural education. *Archnet-IJAR*, *16*(1), 184-202.

Nunnally, J. C., & Bernstein, I. H. (2007). *Psychometric theory* (3rd ed.). McGraw-Hill.

Schön, D. (1992). *The reflective practitioner: how professionals think in action* (1st ed.). Routledge.

Tandon, U., Mittal, A., Bhandari, H., & Bansal, K. (2022). E-learning adoption by undergraduate architecture students: facilitators and inhibitors. *Engineering, Construction and Architectural Management*, *29*(10), 4287-4312.

Tavakol, M., & Dennick, R. (2011). Making sense of Cronbach's alpha. *International Journal of Medical Education*, *2*, 53-55.

Travis, S. (2022). Onsite/online: a case study approach pivots to virtual and back with new strategies learned. *Architecture MPS*, *22*(1), 1-13.

Varma, A., & Jafri, M. S. (2021). COVID-19 responsive teaching of undergraduate architecture programs in India: learnings for post-pandemic education. *Archnet-IJAR*, *15*(1), 189-202.

Xu, Y., Yeung, J. F., Chan, A. P., Chan, D. W., Wang, S. Q., & Ke, Y. (2010). Developing a risk assessment model for PPP projects in China – a fuzzy synthetic evaluation approach. *Automation in Construction*, 19(7), 929-943.

Yu, R., Ostwald, M. J., Gu, N., Skates, H., & Feast, S. (2022). Evaluating the effectiveness of online teaching in architecture courses. *Architectural Science Review*, *65*(2), 89-100.

Zhao, X., Hwang, B. G., Low, S. P., & Wu, P. (2014). Reducing hindrances to enterprise risk management implementation in construction firms. *Journal of Construction Engineering and Management*, *141*(3), 04014083.

Zhao, X., Hwang, B. G., & Low, S. P. (2015). Enterprise risk management in international construction firms: drivers and hindrances. *Engineering, Construction and Architectural Management*, *22*(3), 347-366.

Zhou, Y., Yang, Y., & Yang, J. B. (2019). Barriers to BIM implementation strategies in China. *Engineering, Construction and Architectural Management*, *26*(3), 554-574.

A Multi-Criteria Decision-Making Approach for Curriculum Development in Project and Construction Management Graduate Programs

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Abstract

Due to the dynamic nature of the Architecture, Engineering, and Construction (AEC) industry, project and construction management (PCM) professionals have to excel in both theoretical understanding and managerial capabilities. Accordingly, PCM programs become pivotal in preparing graduates with the essential knowledge and foundational skills for their future employment. However, the absence of a standardized approach for identifying the core skills, competencies, and knowledge of PCM professionals leads to significant differences among the graduates of those programs. This study proposes a multi-criteria decision-making approach for curriculum development of PCM graduate programs. A judgmental sampling procedure targets well-known PCM academics and professionals to identify the core skills, competencies, and knowledge of PCM graduates. The findings of this study can assist PCM educators and curriculum developers in developing, reviewing, and refining the objectives of PCM graduate programs.

Keywords: *curriculum development, graduate education, multi-criteria decision-making, project and construction management.*

Introduction

Project management often used interchangeably with construction management (CM) within the Architecture, Engineering, and Construction (AEC) domain, encompasses the application of specialized knowledge, skills, tools, and techniques to deliver valuable outcomes to the project stakeholders (PMI, 2017). Professional services offered by construction managers focus on effectively managing the project scope, schedule, cost, quality, and safety in construction projects. CM incorporates enhancing the built environment by interdisciplinary professionals collaborating with academics to address the evolving requirements of the global society (CIOB, 2019). Consequently, beyond its professional realm, CM stands as a recognized academic field and a domain of research that continuously evolves and undergoes augmentation throughout its history (Pietroforte & Stefani, 2004; Arditi & Polat, 2010; Harty & Leiringer, 2017).

The early examples of CM programs emerged in the United States and were swiftly followed by the global community, offering quality education at both undergraduate and graduate levels. Presently, a multitude of undergraduate and graduate programs worldwide are dedicated to training future professionals specializing in various aspects of construction management, including project scheduling, budget control, safety enforcement, quality assurance, and dispute resolution. A recent study by Tezel and Cakmak (2024) identified 18 high-rank universities from the QS Top Universities list and examined their curricula to determine the core modules involved in CM education (see Figure 1). Their study advocates that project and construction management in general terms, contemporary management practices, scheduling and time management, cost management and financial issues, legal and contractual issues together with dispute resolution, prevalent information technologies, sustainability and environmental issues, professional practice and ethics, and thesis/dissertation research are the primary courses covered in a typical CM program (Tezel & Cakmak, 2024).

	Project and Construction	Contemporary Mng	Decision Making	Cost Management	Time Management	Quality Management	Risk Management	Design Management	Legal & Contractual	Financial Issues	Information Technologies	Construction	HR & Org. Behaviour	Health, Safety, and	Sustainability, Energy, &	Prof. Practice & Ethics	Research & Thesis	Seminar
Chalmers University of Technology, Sweden	•			•				•	•	•			•		•		•	
Delft University of Technology, Netherlands	•	•		•			•	•	•	•	•	•	•			•	•	
Illinois Institute of Technology, United States		•	•						•			•						
Istanbul Technical University, Turkey	•	•	•	•	•	•	•		•	•	•		•		•	•	•	•
Michigan State University, United States	•	•		•	•				•	•	•				•	•	•	
Middle East Technical University, Turkey	•	•		•	•		•		•	•	•	•		•	•	•	•	•
National University of Singapore, Singapore	•			•	•			•	•	•	•					•	•	
Texas A&M University, United States	•	•		•	•		•		•	•	•	•			•	•	•	•
The University of Melbourne, Australia	•	•		•	•		•	•	•	•	•	•	•		•	•	•	
The University of New South Wales, Australia	•	•		•	•		•		•	•	•				•	•	•	•
Tsinghua University, China	•	•	•	•					•	•						•	•	
Universitat Politècnica de Catalunya-BarcelonaTech, Spain	•	•	•	•	•	•			•	•	•		•		•		•	
University College London, England	•	•		•					•	•	•		•		•	•	•	
University of California, Berkeley, United States		•			•				•		•				•		•	•
University of Cambridge, England	•	•		•	•				•	•		•				•		
University of Michigan-Ann Arbor, United States	•	•	•	•	•		•			•	•	•			•	•	•	•
University of Reading, England	•	•		•				•	•	•	•	•	•		•	•	•	
University of Salford, England	•			•	•		•		•	•				•	•	•	•	

Note. Mng. denotes Management, HR denotes Human Resources, Org. denotes Organizational, Env. denotes Environment, and Prof. denotes Professional

Figure 1: Top PCM graduate programs and core subject areas (adopted from Tezel and Cakmak (2024)).

While a thorough academic understanding is essential (Edum-Fotwe & McCaffer, 2000), the core of CM education also involves cultivating diverse skills and competencies (Pathuri et al., 2022; Posillico et al., 2023). However, the innately unique characteristics of construction projects necessitate academic programs to offer only a broad perspective, thereby requiring CM professionals to enhance not only their knowledge but also managerial skills through experiencing a myriad of different cases throughout their careers. The two principal accrediting bodies for the built environment and construction programs, the Chartered Institute of Building (CIOB) and the American Council for Construction Education (ACCE) identify the key skills and competencies for master's program graduates. For instance, CIOB (2019) indicates that critical thinking and creativity, complex problem solving and decision making, effective communication, competent use of computer applications, leadership, industry analysis, and learning from industry practices are the required skill outcomes for all built environment master's programs graduates, and adds technical, legal, advanced project management, and high-level planning and programming skills for project management master's programs.

Likewise, ACCE (2021) expects CM master's programs to equip graduates with communications, critical thinking, problem-solving, decision-making, research, advanced communication technology, professional ethics, advanced construction management practices, risk management, and leadership skills.

In today's world, technological developments and economic dynamics are evolving the AEC industry landscape by proposing brand-new business methodologies, updating regulatory customs, and introducing new sector forces. As a result, CM professionals are expected to have profound knowledge and demonstrate managerial duties to adapt to the ever-changing conditions of the industry. Scholars suggest the PCM programs reassess and restructure their curriculum to adapt and respond to these drivers (Ahmed et al., 2014; Benhart & Shaurette, 2014; Wu et al., 2015; Vaz-Serra & Mitcheltree, 2021), which claimed to be lacking (Posillico et al., 2021). In response to this call, the present study proposes a multi-criteria decision-making (MCDM) framework to develop a PCM graduate curriculum based on core skills, competencies, and knowledge. The major objective of this research is to ensure that the graduates have the fundamental knowledge and the most valued abilities needed for their future careers.

Research Methodology

The Decision-Making Process

In this study, instead of using intuitive and potentially biased decisions made by decision-makers (DMs), an MCDM-based framework is proposed to aid DMs in prioritizing the core skills, competencies, and knowledge of PCM graduates. The proposed decision-making process involves three main stages: (1) structuring the problem, (2) constructing the decision model, and (3) analyzing the model.

In the decision environment, knowledge areas were regarded as alternatives, while the core skills and competencies used to evaluate these knowledge areas were specified as criteria. While there is a wealth of literature devoted to identifying the essential managerial skills and competencies, most studies tend to focus on management skills in a broad sense, rather than specifically addressing CM skills and competencies. Therefore, this research study adopts the skills and competencies outlined by CIOB and ACCE. Accordingly, eight criteria (skills and competencies valued by the AEC industry), namely, (COMM) communication, (CRIT) critical thinking and creativity, (ANLY) analysis and research, (PROB) problem-solving and decision-making, (CMNG) construction management practices, (TECH) technology use, (ETHC) professional ethics, and (LEAD) leadership were taken into account during the decision-making process. Alternatives were identified as nine core knowledge areas in PCM programs, namely, (INTR) introduction to PCM, (MANG) contemporary management practices, (DECM) decision making, (COST) cost management, (TIME) time management, (QUAL) quality management, (RISK) risk management, (LEGL) legal and contractual issues, and (FINA) financial issues. Although a previous study by Tezel and Cakmak (2024) identified eighteen subject areas taught in PCM programs, this research study concentrated on the top nine courses, as it was noted that comparing more than seven objectives at once (plus or minus two) confuses the decision maker (Bahurmoz, 2006). Thus, as shown in Figure 2, the decision hierarchy was structured, including the goal, eight criteria (skills and competencies), and nine alternatives (knowledge areas).

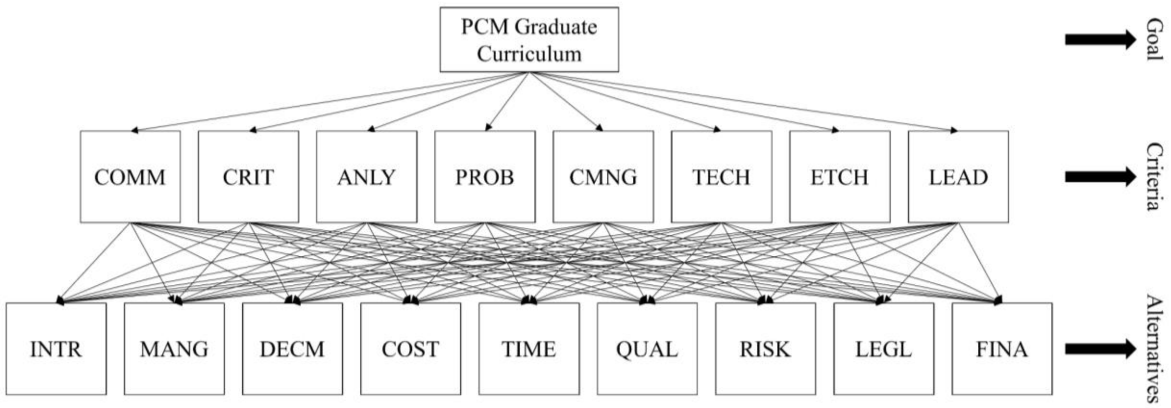

Figure 2: The decision hierarchy.

Profile of Decision-Makers

The authors interacted with seven academics positioned as DMs with expertise in PCM graduate education. DMs were selected from Istanbul Technical University, a well-established institution offering multiple PCM postgraduate programs in architecture and civil engineering. While acknowledging the potential limitation of reduced representativeness of the results due to targeting a singular institution, this paper intentionally focuses on using the MCDM method for curriculum development. As a result, this paper serves as a pilot study for further research on PCM curriculum development using the MCDM method.

A total of seven academics, four from the Department of Architecture and the remaining three from the Department of Civil Engineering, were selected to participate in the survey. Table 1 below represents the decision-maker characteristics. DM1 and DM2 were professors with more than 35 years of experience in teaching and conducting research in the PCM field. DM3, DM4, and DM5 were associate professors with 17, 19, and 21 years of academic experience, respectively. Finally, DM6 and DM7 were PhD holders with eight years of experience in teaching and research.

Table 1. Decision maker characteristics.

Respondent ID	Title	Department	Experience
DM1	Professor	Architecture	35+ years
DM2	Professor	Architecture	35+ years
DM3	Associate Professor	Architecture	17 years
DM4	Associate Professor	Civil Engineering	19 years
DM5	Associate Professor	Civil Engineering	21 years
DM6	Dr	Architecture	8 years
DM7	Dr	Civil Engineering	8 years

Analytic Hierarchy Process

This paper used the Analytic Hierarchy Process (AHP) method, first introduced by Saaty in 1980, to solve MCDM problems. In accordance with AHP steps, a pairwise comparison questionnaire was directed to assess the judgments of the DMs for all possible pairs of elements. A special nine-point scale is used to perform pairwise comparisons where 1 represents that two items have the same impact; 3 represents moderately more dominance of the first item on the second; 5, 7, and 9 represent strongly more, very strongly more, and overwhelming dominance of the first item on the second item, respectively (Saaty, 1980).

The questionnaire assessed DMs' judgments representing the relative influence of criteria and alternatives for all possible pairs. DMs were initially briefed on the purpose of the study and the AHP method. They were provided with the pairwise comparison questionnaire and instructed to complete it independently following the instructions.

Data Analysis and Findings

For the decision model analysis, the geometric means of each paired comparison judgment were calculated to determine the overall group judgments. After aggregating the DMs' judgments, the AHP method was applied to reveal the relative priorities of the criteria and the alternatives. Accordingly, the computations of the AHP method were applied for each pairwise comparison matrix. Table 2 shows the aggregated pairwise matrix and relative priorities of criteria within the decision model. The consistency ratio of this matrix was calculated and found as 0.04, which is lower than 0.10. Thus, the matrix was found to be consistent.

Table 2. Aggregated pairwise matrix and relative priorities of criteria.

Criteria	COMM	CRIT	ANLY	PROB	CMNG	TECH	ETHC	LEAD	Priorities
COMM	1.000	1.757	0.435	0.174	0.611	1.390	0.560	0.412	0,074
CRIT		1.000	0.705	0.416	0.987	1.132	0.530	0.253	0,071
ANLY			1.000	0.517	0.781	1.935	0.648	0.368	0,103
PROB				1.000	2.083	2.254	0.808	0.637	0,191
CMNG					1.000	2.498	0.711	0.639	0,113
TECH						1.000	0.665	0.289	0,064
ETHC							1.000	1.944	0,174
LEAD								1.000	0,205

According to the findings, the "leadership" (LEAD) criteria has the highest priority for the curriculum development of PCM graduate programs. The "problem-solving and decision-making" (PROB) and the "professional ethics" (ETHC) are the second and third criteria with high priorities, showing that they also have significant importance for curriculum development. It is followed by the "construction management practices" (CMNG) and the "analysis and research" (ANLY) criteria. On the other hand, the "communication" (COMM), the "critical thinking and creativity" (CRIT), and the "technology use" (TECH) criteria have relatively lower impacts on curriculum development.

AHP calculations were repeated for each alternative's pairwise comparison matrix concerning eight criteria. For each criterion, eight pairwise comparison matrices were tabulated. Each matrix's consistency ratio was calculated and found consistent with values lower than 0.10. Table 3 represents the global preferences for alternatives with their relative priorities.

Table 3. Relative priorities of alternatives.

Rank	Alternatives	Relative Priorities
1	Decision Making (DECM)	0.2087
2	Contemporary Management Practices (MANG)	0.1429
3	Legal and Contractual Issues (LEGL)	0.1298
4	Risk Management (RISK)	0.1026
5	Time Management (TIME)	0.0921
6	Cost Management (COST)	0.0918
7	Financial Issues (FINA)	0.0848
8	Quality Management (QUAL)	0.0819
9	Introduction to PCM (INTR)	0.0654

As presented, the most preferred knowledge area is “Decision Making” (DECM), with 20.84%, followed by “Contemporary Management Practices” (MANG), with 14.29%. The subsequent knowledge areas are “Legal and Contractual Issues” (LEGL) (12.98%), “Risk Management” (RISK) (10.26%), “Time Management” (TIME) (9.21%), “Cost Management” (COST) (9.18%), “Financial Issues” (FINA) (8.48%), and “Quality Management” (QUAL) (8.19%). The least preferred knowledge area is “Introduction to PCM” (INTR), with 6.54%.

The findings reveal remarkable differences between the foundational knowledge domains delineated by PCM education experts and the existing curriculum of the PCM programs. The most striking difference is the variance observed within the Decision Making (DECM) topic. According to the AHP results, decision-making occupies the top priority knowledge domain in a PCM graduate curriculum. Nonetheless, most programs do not offer a module dedicated explicitly to decision-making. Conversely, an opposite scenario emerges within the Introduction to PCM (INTR) topic. Being the second most frequent course in programs’ curricula, Project and Construction Management exhibits the lowest priority compared to the other domains of PCM. While an introductory course may not be directly attributed to the PCM profession, it serves as a foundation for students intending to specialize in PCM with a comprehensive understanding of the subject matter.

Conclusion

Being a construction manager necessitates the blending of advanced expertise in construction with a range of supervisory capabilities. While historical precedents in CM education have established foundational programs, the evolving nature of the AEC industry necessitates a continuous adaptation of curricula to equip professionals with the diverse knowledge, skills, and competencies demanded by the industry. As technological advancements and economic shifts reshape the AEC landscape, the need for responsive and adaptable CM programs becomes increasingly evident. Therefore, this study proposes an MCDM approach to curriculum development, aimed at ensuring that PCM graduates possess the essential knowledge and valued competencies to thrive in the dynamic and demanding environments of their future careers.

Based on the study findings it is evident that leadership, problem-solving and decision-making, and professional ethics emerge as the foremost important skill sets when shaping the PCM graduate curriculum. Moreover, the analysis reveals that among the various knowledge domains examined, courses related to decision-making and contemporary management practices are the most valued ones, aligning with the anticipated significance of leadership and decision-making as high-level managerial abilities. Other courses, including legal and contractual issues, risk management, time management, cost management, financial issues, and quality management exhibit relatively low scores, reflecting their alignment with tactical management roles. Finally, introductory courses exhibit the lowest score, because they cannot be directly attributed to a specific managerial skill.

The findings of this study underscore the necessity for prioritizing particular knowledge areas, skills, and competencies over others when designing and refining the PCM graduate curricula. The insights of seven academics offer valuable perspectives, yet they remain partial when aligning the objectives of PCM courses with the evolving needs and expectations of the AEC industry. Future research should prioritize (1) broader engagement from well-respected institutions and industry leaders, (2) deeper exploration to identify PCM-specific skills and knowledge, and (3) the application of diverse MCDM methodologies to optimize curriculum development processes.

References

Ahmed, S. M., Yaris, C., Farooqui, R. U., & Saqib, M. (2014). Key attributes and skills for curriculum improvement for undergraduate construction management programs. *International Journal of Construction Education and Research*, *10*(4), 240-254.

American Council for Construction Education (2021). *Standards and criteria for the accreditation of construction education programs (Document 103)*. https://www.acce-hq.org/file-share/48e86a14-cae9-4775-9334-831c94b714f6

Arditi, D., & Polat, G. (2010). Graduate education in construction management. *Journal of Professional Issues in Engineering Education and Practice, 136*(3), 175-79.

Bahurmoz, A. M. (2006). The analytic hierarchy process: a methodology for win-win management. *Economics and Administration, 20*(1), 3-16.

Benhart, B. L., & Shaurette, M. (2014). Establishing new graduate competencies: Purdue University's construction management curriculum restructuring. *International Journal of Construction Education and Research, 10*(1), 19-38.

Chartered Institute of Building (2019). *The education framework for master's degree programs*. https://www.ciob.org/learning-providers/education-framework

Edum-Fotwe, F. T., & McCaffer, R. (2000). Developing project management competency: perspectives from the construction industry. *International Journal of Project Management, 18*, 111-124.

Harty, C., & Leiringer, R. (2017). The futures of construction management research. *Construction Management and Economics, 35*(7), 392-403.

Pathuri, R. T., Killingsworth, J., & Mehany, M. S. H. M. (2022). Knowledge, skills, and abilities for senior-level construction managers: a US Industry-based Delphi study. *International Journal of Construction Education and Research, 18*(3), 234-250.

Pietroforte, R., & Stefani, T. P. (2004). ASCE Journal of Construction Engineering and Management: review of the years 1983–2000. *Journal of Construction Engineering and Management, 130*(3), 440-448.

Posillico, J. J., Edwards, D. J., Roberts, C., & Shelbourn, M. (2021). Curriculum development in the higher education literature: a synthesis focusing on construction management programmes. *Industry and Higher Education, 36*(4), 456-470.

Posillico, J. J., Edwards, D. J., Roberts, C., & Shelbourn, M. (2023). A conceptual construction management curriculum model grounded in scientometric analysis. *Engineering, Construction and Architectural Management, 30*(9), 4143-4170.

Project Management Institute (PMI) (2017). *A guide to the project management body of knowledge (PMBOK Guide)* (6th ed.). Project Management Institute.

Saaty, T. L. (1980). *Multicriteria decision making: the analytic hierarchy process*. RWS Publications.

Tezel, E., & Cakmak, P. I. (2024). Skills, competencies and knowledge for construction management graduates. *A|Z ITU Journal of the Faculty of Architecture, 21*(1), 1-14.

Vaz-Serra, P., & Mitcheltree, H. (2021). Understanding the key master of construction project management graduate competencies required to meet industry needs in Australia. *International Journal of Construction Education and Research, 17*(3), 222-241.

Wu, P., Feng, Y., Pienaar, J., & Zhong, Y. (2015). Educational attainment and job requirements: exploring the gaps for construction graduates in Australia from an industry point of view. *Journal of Professional Issues in Engineering Education and Practice, 141*(4), 06015001.

BIM Education in Undergraduate Architecture Programs: A Systematic Literature Review

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Abstract

As the industry changes, today's undergraduate students will need to employ BIM technology in their professional careers. Universities offering construction engineering and management education are attempting to include building information modeling (BIM) principles and abilities into their degree programs as BIM is becoming more common practice in the construction industry. This paper aims to systematically review the undergraduate architectural departments in Turkey, which have BIM education in their curriculum. However, there is lack of BIM education in the undergraduate curriculum. According to the research, significant amount of research has documented the tactics architecture, engineering and construction (AEC) programs took to include BIM in their curriculum. This was spurred by the realization in both industry and academics that BIM education in university curriculum is a crucial necessity for addressing educational expectations of the industry. Finally, literature-based framework of BIM curriculum design methodologies is presented in this study, that may serve as a guide for future research by BIM educators and researchers when developing or evaluating their BIM curriculum.

Keywords: *BIM education, undergraduate, architecture.*

Introduction

BIM has revolutionized the AEC industries by providing a digital representation of buildings which enhances collaboration, efficiency, and integration throughout the project lifecycle, from design to operation (Azhar et al., 2012). The importance of BIM lies in its ability to create digital representations of physical and functional characteristics of places, facilitating a more integrated and collaborative approach to building design and construction. BIM supports the entire project lifecycle, from conceptualization through construction to facility operations, enhancing efficiency, reducing costs, and improving the quality of built environments.

Introducing BIM education at the undergraduate level is essential for equipping future professionals with the skills demanded by the evolving AEC industries. This includes not only the technical skills of using BIM software but also competencies in collaborative work processes and data management, which are critical for driving innovation and efficiency in building projects (Kim et al., 2013). By integrating BIM into the curriculum, educational institutions equip students with essential skills that are increasingly demanded in the industry.

Students learn not only the technical aspects of using BIM software but also gain an understanding of collaborative work processes, interdisciplinary communication, and data management. This education helps in nurturing a workforce capable of driving innovation and efficiency in building projects.

Educating undergraduates about BIM also promotes a deeper understanding of sustainable design and construction practices, as BIM enables more accurate simulations of building performance. This can lead to better decisions about energy use, materials, and construction methods, ultimately contributing to the creation of more sustainable and resilient built environments. As the construction industry continues to evolve, BIM education will be vital in ensuring that future professionals are well-prepared to meet the challenges of modern construction and infrastructure development.

BIM facilitates accurate simulations of building performance, promoting sustainable design and construction practices. This technology helps in making informed decisions regarding energy use, materials, and construction methods, thus contributing to more sustainable and resilient built environments (Chen et al., 2019). Investigating Building Information Modeling (BIM) undergraduate education serves several key purposes that are crucial for the advancement and adaptation of this technology in the construction and architecture industries. Here are the primary objectives of conducting such an investigation:

1.Curriculum Development: The main purpose of investigating BIM in undergraduate education is to assess and enhance the existing curriculum. This helps ensure that it aligns with the latest industry standards and technological advancements. An investigation can identify gaps in current educational offerings and suggest necessary updates or additions to provide students with a comprehensive understanding of BIM.

2.Industry Needs Alignment: By examining how BIM is taught at the undergraduate level, educational institutions can align their programs more closely with the specific needs of the construction and architecture sectors. This involves understanding the skills and knowledge that employers expect from graduates, ensuring that students are job-ready upon completing their degrees.

3.Technological Integration: Investigating BIM education helps in understanding how effectively new technologies and software are integrated into academic programs. It is crucial to keep educational standards up-to-date with technological advancements to foster a tech-savvy workforce.

4.Interdisciplinary Collaboration: BIM involves multiple disciplines working together seamlessly. An investigation can explore how undergraduate programs are preparing students for collaborative work environments. This includes teaching communication, project management, and teamwork skills alongside technical BIM training.

5.Innovation and Research: Educational investigations can spur innovation and research in BIM by identifying new areas for academic inquiry and development. This can lead to pioneering research projects and collaborations with industry partners, pushing the boundaries of what BIM can achieve.

6.Global Competitiveness: With BIM becoming a global standard, investigating its role in undergraduate education ensures that students are competitive in international job markets. This helps in raising the global standing of educational institutions and their graduates.

By focusing on these areas, BIM undergraduate education can significantly contribute to enhancing the quality of education and its relevance to the fast-evolving needs of the architecture, engineering, and construction industries.

Methodology of the Research

This paper undertakes a two-step investigation to evaluate the integration of Building Information Modeling (BIM) within undergraduate architecture programs in Turkey. In the first phase, the study meticulously examines the curricula of all architecture departments at 62 public universities accredited by the Higher Education Council (YÖK). This comprehensive review focuses on identifying the presence of BIM concepts beyond the usage of digital presentation tools in their syllabus, finding no significant integration of BIM.

The second phase of the research involves a detailed literature review conducted using the Scopus database. Keywords such as “BIM,” “undergraduate,” and “architecture” are utilized to locate relevant studies, resulting in 23 articles that are thoroughly analyzed. The findings from these articles are systematically presented in the results section of the paper, offering insights into the current academic discourse surrounding BIM education at the undergraduate level in architecture.

Results

Results of the literature review is shown below.

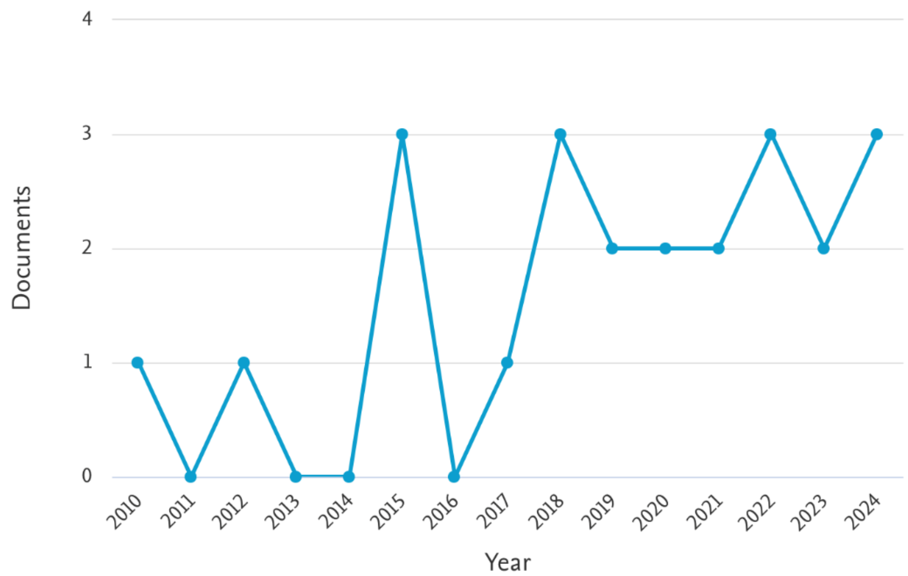

Figure 1: Documents by year.

Figure 1 indicated that publication on education of BIM is so few, recent years 2 articles published on average.

On Figure 2 below, represents the published documents' country.

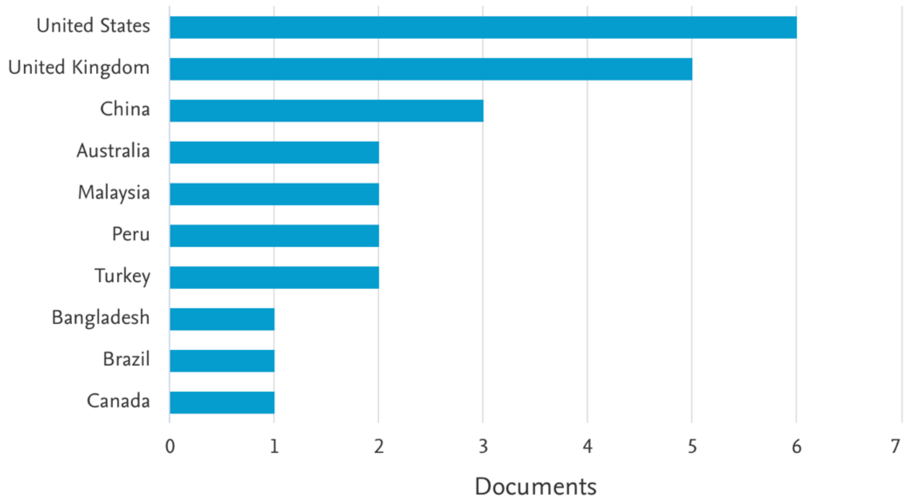

Figure 2: Documents published by countries.

From Turkey two publications are investigated:

1. *Ağırbaş, A.* Teaching construction sciences with the integration of BIM to undergraduate architecture students

   Summary: The study demonstrates that integrating Building Information Modeling (BIM) with construction science in course teaching effectively enhances student learning. The research is based on a case study based on a lesson outcome which was done in 2019 with 32 students using Revit. Statistical analysis and student questionnaires confirm that students not only learn to use BIM tools like Revit but also gain a deep understanding of construction concepts simultaneously. For instance, they explore relationships between structural elements like columns and beams within the BIM software, which also helps clarify their placement and interaction in a real-world setting.

   BIM software provides students with dynamic views (plan, section, and perspective) that aid in understanding complex architectural systems, such as the configurations of stairs and roof types. This approach not only bridges the gap between theoretical knowledge and practical application but also increases student productivity by making them familiar with tools that are increasingly important in the professional architectural field.

   Moreover, students' exposure to BIM during their undergraduate studies prepares them for faster integration into professional environments where BIM is a standard practice. They start creating personal libraries of architectural details through Revit during the course, facilitated by cloud technology that allows easy sharing and collaboration among classmates. This helps in accumulating a diverse range of construction techniques and standards applicable globally, enhancing the practical utility of their architectural education.

2. *İyican, B. et.al.* A studio experience on parametric modelling approaches (Full text is not available.)

   Summary of abstract: Parametric modeling has had a huge impact on architectural practices in the digital age, moving the field from conceptual concepts to building applications and even affecting architectural education. Parametric modeling approaches, such as Building Information Modeling (BIM) and Computer Aided Design (CAD), are widely used in professional contexts, but are primarily taught at the Master's or PhD levels, with less emphasis on undergraduate education. Karabük University launched studio practices centered on parametric modeling in response to the realization that students require early exposure to these cutting-edge tools in order to be better prepared. These studios teach students through hands-on exercises using programs like Revit Architecture and different plug-ins. With a discussion of the software's contributions to learning outcomes, future directions, and the educational impact, this approach seeks to improve students' comprehension and competency in parametric modeling.

A Syllabus Suggestion

Investigations into how BIM is taught can help educational institutions align their programs with the specific needs of the construction and architecture sectors, ensuring that graduates are ready to meet the demands of the industry immediately upon completing their degrees (Wang et al., 2013). By addressing these areas, BIM undergraduate education can significantly enhance the quality of education and its relevance to the rapidly evolving needs of the architecture, engineering, and construction industries. Research into BIM undergraduate education helps in curriculum development by aligning educational offerings with the latest industry standards and technological advancements. This ensures that students receive a comprehensive education that prepares them adequately for their professional roles (Rowlinson et al., 2010). Creating a syllabus for teaching Building Information Modeling (BIM) to undergraduate architecture students involves outlining key learning objectives, course content, methodologies, and assessments that will equip students with the necessary skills and knowledge in BIM. A structured syllabus template focused on delivering comprehensive BIM education is shared below:

Course Title: Introduction to Building Information Modeling (BIM)

Credit Hours: 4

Prerequisites: Basic Computer Skills, Building Technology Classes

Course Description:

This course introduces undergraduate architecture students to the fundamentals of Building Information Modeling (BIM), emphasizing the integration of architecture, engineering, and construction (AEC) disciplines. Students will learn how to use BIM software and tools to create, manage, and document building designs. The course covers theoretical concepts, practical skills, and collaborative workflows essential for the effective use of BIM in professional practice.

Learning Objectives:

1. Understand the principles and concepts underlying BIM and its impact on the AEC industry.
2. Develop and manipulate 3D models of buildings using BIM software.
3. Apply BIM processes for integrated project delivery, including collaboration among various stakeholders.
4. Generate and manage documentation, schedules, and simulations derived from BIM models.
5. Critically assess the role of BIM in sustainable design and construction practices.

Course Content:

•Week 1-2: Introduction to BIM, History and evolution of BIM, BIM in the AEC industry: current practices and future trends

•Week 3-4: BIM Software and Tools, Overview of BIM software (e.g., Revit, ArchiCAD, Navisworks), Basic modeling techniques: creating and editing geometric and parametric elements

•Week 5-6: BIM for Design and Documentation, From conceptual design to detailed construction documents, Generating plans, sections, elevations, and schedules from BIM models

•Week 7-8: BIM for Collaboration and Project Management, Collaborative workflows and interoperability between different BIM tools, Introduction to Common Data Environments (CDE) and BIM standards (e.g., ISO 19650)

•Week 9-10: Advanced BIM Applications, BIM for sustainable design: energy analysis, daylighting studies, Using BIM for cost estimation, scheduling, and construction management

•Week 11-12: BIM Implementation and Case Studies, Strategies for implementing BIM in architectural practice, Case studies: successful BIM projects in architecture

Teaching Methodology:

- Lectures to introduce theoretical concepts
- Hands-on training sessions in computer labs
- Group projects to simulate real-world BIM collaborative workflows
- Guest lectures by industry professionals

Textbooks and Resources:

•Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2018). BIM Handbook: A Guide to Building Information Modeling for Owners, Designers, Engineers, Contractors, and Facility Managers. 3rd ed. Wiley.

•Additional readings and resources will be provided on the course website.

Software Requirements:

Students are required to have access to BIM software (e.g., Autodesk Revit, Graphisoft ArchiCAD) either through the university's computer labs or personal computers.

Conclusion

The lack of Building Information Modeling (BIM) in undergraduate education in architecture, engineering, and construction (AEC) is a notable gap that may hinder the preparedness of graduates entering a rapidly evolving professional landscape. BIM technology, recognized for its ability to streamline project management and integrate various phases of building design and construction, is increasingly becoming a standard practice within the industry. Its absence at the undergraduate level means that students may miss out on developing essential skills that are highly valued in the workforce.

This gap in education could lead to a workforce that is less efficient and less innovative, as the benefits of BIM—such as enhanced coordination, reduced waste, improved scheduling, and cost savings—are not fully realized. Furthermore, students lacking BIM training may find themselves at a competitive disadvantage in the job market, where employers increasingly expect proficiency in these modern digital tools as a basic qualification.

Incorporating BIM training into undergraduate curricula could not only enhance the educational experience by providing students with hands-on, practical skills but also align academic programs with industry needs. This alignment is crucial for fostering an innovative, agile, and technically proficient workforce capable of leading the future of the AEC industries.

Thus, it is imperative for educational institutions to adapt to these changes, not only to enhance the employability of their graduates but also to contribute to the advancement of industry standards and practices. By integrating BIM into their programs, universities and colleges can ensure that their students are better prepared to meet the challenges of modern architectural and construction environments, ultimately leading.

References

Agirbas, A. (2020). Teaching construction sciences with the integration of BIM to undergraduate architecture students. *Frontiers of Architectural Research*, 9(4), 940–950.

Ao, Y., Liu, Y., Tan, L., Zhao, L., & Martek, I. (2021). Factors driving BIM learning performance: Research on China's sixth national BIM graduation design innovation competition of colleges and universities. *Buildings*, 11(12), 616.

Ao, Y., Peng, P., Li, J., Bahmani, H., & Wang, T. (2022). What determines BIM competition results of undergraduate students in the architecture, engineering and construction industry? *Behavioral Sciences*, 12(10), 360.

Azhar, S., Khalfan, M., & Maqsood, T. (2012). Building information modelling (BIM): now and beyond. *Australasian Journal of Construction Economics and Building*, 12(4), 15-28.

Babatunde, S. O., & Ekundayo, D. (2019). Barriers to the incorporation of BIM into quantity surveying undergraduate curriculum in the Nigerian universities. *Journal of Engineering, Design and Technology*, 17(3), 629–648.

Babatunde, S. O., Ekundayo, D., Babalola, O., & Jimoh, J. A. (2018). Analysis of the drivers and benefits of BIM incorporation into quantity surveying profession: Academia and students' perspectives. *Journal of Engineering, Design and Technology*, 16(5), 750–766.

Benner, J., & McArthur, J. J. (2019). Data-driven design as a vehicle for BIM and sustainability education. *Buildings*, 9(5), 103.

Callahan, M. P. (2015). Teaching leadership skills: A case study in active-learning pedagogy. *International Journal of Interdisciplinary Educational Studies*, 9(2), 13–20.

Chen, Y., Yin, Y., Browne, G. J., & Li, D. (2019). Adoption of building information modeling in Chinese construction industry. *Engineering, Construction and Architectural Management*.

Dan, W., Ismail, R., Yen, T. J., Shafiei, M. W. M., & Yee, H. C. (2023). Digital technology fluency and BIM learning environment in undergraduate construction management. *International Journal on Advanced Science, Engineering and Information Technology*, 13(1), 235–249.

Del Savio, A. A., Galantini Velarde, K., Díaz-Garay, B., & Valcárcel Pollard, E. (2022). A methodology for embedding building information modelling (BIM) in an undergraduate civil engineering program. *Applied Sciences (Switzerland)*, 12(23), Article 12203.

Espinoza, V. P. R., Cárdenas-Salas, D., Cabrera, A., & Coronel, L. (2021). Virtual reality and BIM methodology as teaching-learning improvement tools for sanitary engineering courses. *International Journal of Emerging Technologies in Learning*, 16(6), 20–39.

Ghosh, A., Parrish, K., & Chasey, A. D. (2015). Implementing a vertically integrated BIM curriculum in an undergraduate construction management program. *International Journal of Construction Education and Research*, 11(2), 121–139.

Gunasagaran, S., Karuppannan, G., Mari, T., Kuppusamy, S., & Srirangam, S. (2023). Architecture students' attitude towards sustainability and the use of digital simulation. *Journal of Engineering Science and Technology*, 18, 82–95.

Hossain, S. T., & Bin Zaman, K. M. U. A. (2022). Introducing BIM in outcome based curriculum in undergraduate program of architecture: Based on students perception and lecture-lab combination. *Social Sciences and Humanities Open*, 6(1), Article 100301.

Huang, Y. (2018). Developing a three-level framework for building information modeling education in construction management. *Universal Journal of Educational Research*, 6(9), 1991–2000.

İyican, B., Dinçer, E., & Bektaş, I. (2015). A studio experience on parametric modelling approaches. *Turkish Online Journal of Educational Technology*, 2015, 51–60

Jin, R., Yang, T., Piroozfar, P., Hancock, C. M., & Tang, L. (2018). Project-based pedagogy in interdisciplinary building design adopting BIM. *Engineering, Construction and Architectural Management*, 25(10), 1376–1397.

Kim, H., Anderson, K., Lee, S., & Hildreth, J. C. (2013). Generating construction schedules through automatic data extraction using open BIM (building information modeling) technology. *Automation in Construction*, 35, 285-295.

Obi, L. I., Omotayo, T., Ekundayo, D., & Oyetunji, A. K. (2024). Enhancing BIM competencies of built environment undergraduates students using a problem-based learning and network analysis approach. *Smart and Sustainable Built Environment*, 13(1), 217–238.

Rowlinson, S., Collins, R., Tuuli, M., & Jia, Y. (2010). Implementation of building information modeling (BIM) in construction: A comparative case study. *AIP Conference Proceedings* (Vol. 1233, No. 1, pp. 572-577). American Institute of Physics.

Sacks, R., & Barak, R. (2010). Teaching building information modeling as an integral part of freshman year civil engineering education. *Journal of Professional Issues in Engineering Education and Practice*, 136(1), 30–38.

Shelbourn, M., Macdonald, J., McCuen, T., & Lee, S. (2017). Students' perceptions of BIM education in the higher education sector: A UK and US perspective. *Industry and Higher Education*, 31(5), 293–304.

Shen, Z., Jensen, W., Wentz, T., & Fischer, B. (2012). Teaching sustainable design using BIM and project-based energy simulations. *Education Sciences*, 2(3), 136–149.

Sotelino, E. D., Natividade, V., & Travassos Do Carmo, C. S. (2020). Teaching BIM and its impact on young professionals. *Journal of Civil Engineering Education*, 146(4), 05020005.

Valbuena-Bermúdez, C., Lozano-Ramírez, N. E., Serrano-Sierra, A., & Granados-León, C. (2024). CAMPUS: A mobile app for construction processes learning and teaching in higher education. *Computer Applications in Engineering Education*. Advance online publication.

Wang, Y., Xue, X., & Li, Y. (2013). A critical review on the impact factors of BIM application. *International Journal of Digital Content Technology and Its Applications*, 7(8), 616-624.

Yang, F., Akanbi, T., Chong, O. W., Chen, Y., & Hubbard, B. J. (2024). Project-based introduction to computing in construction management curriculum: A case study. *Journal of Civil Engineering Education*, 150(1), 05023008.

Teaching the Basic Principles of Lean Approach through Simulation Games: A Systematic Literature Review

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Abstract

Modern construction projects are facing new and more sophisticated challenges, such as increased project complexity, implementation of numerous changes by the client during the execution stage, or operation in uncertain conditions. Numerous publications discuss various approaches and technologies to manage these challenges. One of the proposals is applying a lean approach to construction management. Lean construction introduces a new approach for maximizing value while minimizing waste, facilitating sustainable practices at the same time. However, lean construction is often only partially or incorrectly applied. A basic cause is that site management and workers are not familiar with lean principles, therefore simulation games give better learning outcomes than traditional teaching methods as the former enables active involvement of participants as they are learning. In construction industry, lean simulation games are considered to be an effective mechanism to impart knowledge on various lean concepts in a clear, realistic, and simplified manner. With this in mind, the paper initiated a Systematic Literature Review (SLR) on lean simulation games. Findings showed that lean simulation games are still an important and active topic in recent years. According to the systematic review of the literature, the International Group for Lean Construction (IGLC) serves as a significant contributor to the emergence and dissemination of new and existing lean games and simulations. Moreover, different lean principles concluded from reviewed simulation games but most of them do not hold reduction of waste and analysis of activities as the key learning outcomes.

Keywords: *construction industry, lean approach, simulation games, systematic literature review.*

Introduction

Construction sector strongly affects various other sectors and has a direct impact over various economic, educational, transportation, and other sectors. Therefore, attention should be paid to identify the major challenges in construction sector and their solutions (Dixit et al., 2017). These challenges mainly are low productivity, waste generation, energy consumption, impact on surrounding environment, water usage, and other social and economic issues (Ballard & Howell, 2004). To overcome these challenges and complete a project within budget and on time, innovative project management techniques have to be used (Aziz & Hafez, 2013).

Lean construction is kind of innovation in construction industry as its approach is different from typical conventional one. Lean philosophy includes a set of tools, principles, and production techniques that identify and eliminate waste through continual improvements in processes (Shaqour, 2022). According to Marhani et al. (2013), Lean production system is a collaborative approach of various parameters towards maximization of benefits or production with minimum waste. At the same time, successful implementation of lean construction is dependent on how these lean concepts and principles are being understood, applied, and practiced by stakeholders associated with the construction sector (Bhatnagar et al., 2022). While various terminologies, philosophies, and interpretations of the lean concept have been discussed in the literature, they are arguably only partially understood and applied (Rybkowski et al., 2018).

Teaching methods of the traditional educational system are criticized for neglecting these aspects, since they focus mainly on individual competence. Experts argue that theory alone is not enough to learn lean principles and gain understanding for its practical application. Therefore, experiential learning is recommended (Cisterna et al., 2021). According to Herrera et al. (2019) and Von Heyl (2015), combining theory with simulations or a systematic approach that both teaches and trains lean principles is a good way to reach this objective. As Rybkowski et al. (2008) states: “Lean simulation games offer educational benefits that cannot be found in textbooks”.

To teach lean construction principles using simulation games is not a new approach according to the previous review. Several games have already been successfully developed to impart lean principles. For example, Rybkoswki et al. (2016) have upgraded the “marshmallow simulation” to teach concepts related to target value design. Similarly, teams of practitioners have developed the Villego simulation to mimic the implementation of the Last Planner System (LPS) in the construction of houses (Villego, 2016). Moreover, González et al. (2015) presented a simulation game called LEBSCO as a learning tool to transfer the knowledge of lean production principles into construction. In this context, this paper aims to summarize the lean construction principles used in simulation games as presented in the literature. This summarization can help in determining the most focused principles in simulation games by using a systematic literature review.

Literature Review

Lean Construction Principles

Lean approach, which was first developed in the manufacturing sector, begins to integrate into the construction sector as a new philosophy that aims at improving the construction process efficiency and eliminating activities that do not create any added-value for the customer (Aziz & Hafez, 2013; Bajjou et al., 2017). The lean management concept developed in the 1990s, based on the Toyota Production System (TPS). It is a set of practices, tools and organization solutions implemented since 1948 at Japan’s Toyota Motor Company (Holweg, 2007). The main goal of TPS is the reduction of costs by eliminating processes that don’t bring any value, identified in Japanese by the word muda, or waste (Womack & Jones, 2003). Lean management concepts focus primarily on achieving a continuous flow of value within the production system and on reducing waste by analyzing the activities in a production system to distinguish between value-added activities and non-value-added activities (Sundar et al., 2014).

The construction sector does not differ so much from other industries, and it is also possible to apply the tools and methods of improvement. One way to help manage such projects are the principles and tools of lean management, which enable the comprehensive management of a whole construction process and the gradual improvement of a situation related to construction management in order to eliminate waste (Nahmens & Mullens, 2011). The introduction of the concept to construction began when the traditional theories of production were questioned by researchers (Ulewicz & Ulewicz, 2020). Koskela (1992) proposed the new integrated view of Transformation, Flow, and Value (TFV) theory of production. This tripartite view of production has led to the birth of lean construction as a discipline that subsumes the transformation-dominated contemporary construction management (Aziz & Hafez, 2013).

Lean construction is simply an attempt to apply lean principals that originate from TPS to construction, aiming at managing and improving construction processes with minimum cost and maximum value by considering customer needs (Zhang & Chen, 2016). Among lean principals, "value" is the most important point which can be only defined by customers. In practice, a set of tools need to be adopted in construction projects to achieve a higher level of work performance. Lean construction was implemented first in the operation phase by using Last Planner System (LPS), but little by little Lean Project Delivery System (LPDS) was implemented and in particular Lean Design through the use of different tools such as set based design, target value design and value stream mapping in the design phase (Chuquín et al., 2021).

As shown in Figure 1, there are five fundamental principles for lean thinking, which have to be followed step by step to gain the maximum benefit of the lean success (Marhani et al., 2012; Womack & Jones, 2003):

1. Specify Value: Specify value from customer's own definition and needs and identify the value of activities, which generate value to the end product;
2. Identify the Value Stream: Identify the value stream by elimination of everything, which does not generate value to the end product.
3. Flow: Ensure that there is a continuous flow in the process and value chain by focusing on the entire supply chain.
4. Pull: Use pull in the production and construction process instead of push. This means produce exactly what the customer wants at the time the customer needs it and always prepared for changes made by customer.
5. Perfection: Aims at the perfect solution and continuous improvements. Deliver a product which lives up to customer's needs and expectations within the agreed time schedule and in a perfect condition without mistakes and defects.

The only way to successfully apply these principles is by having a close communication with the customer/client as well as managers, and employees are between. Moreover, Koskela (1992) has summarized lean thinking into eleven principles which are (1) Reduce the share of non-value adding activities (waste); (2) Increase output value through systematic consideration of customer requirements; (3) Reduce variability; (4) Reduce cycle times; (5) Simplify by minimizing the number of steps, parts and linkages; (6) Increase output flexibility; (7) Increase process transparency; (8) Focus control on the complete process; (9) Build continuous improvement into the process; (10) Balance flow improvement with conversion improvement; and (11) Benchmark.

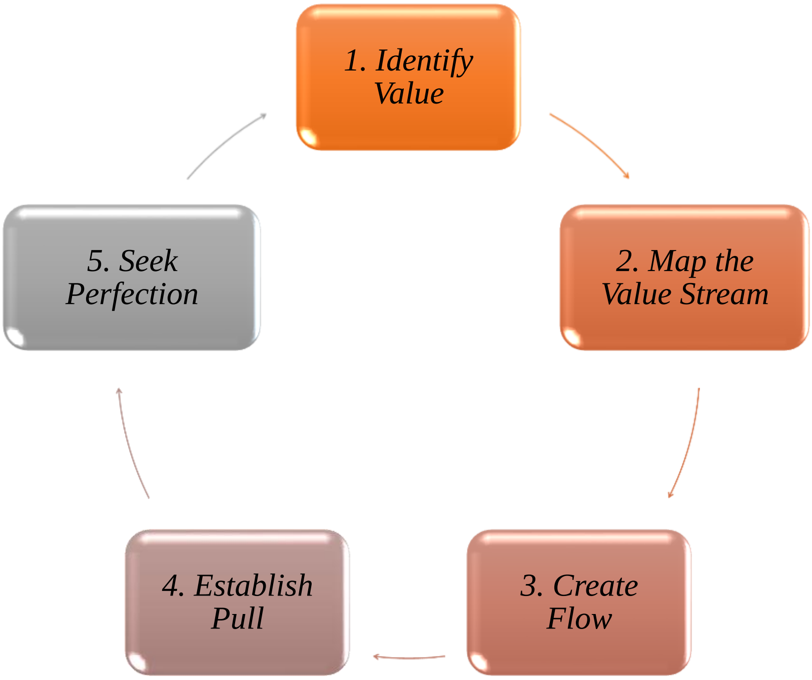

Figure 1: Lean construction principles (Marhani et al., 2012).

Flow is particularly important in construction as construction pertains to complex, one-of-a-kind products and is undertaken usually at the delivery point by a series of repeating but variable activities in multiple locations within a multi-skilled ad-hoc team (Kenley, 2005). This makes the Lean ideal particularly difficult to achieve. An increasing number of construction academics and professionals have been storming the ramparts of conventional construction management in an effort to deliver better value to owners while making real profits (Bataglin et al., 2021). As a result, lean-based tools have emerged and have been successfully applied to simple and complex construction projects. In general, lean construction projects are easier to manage, safer, completed sooner, and cost less and are of better quality (Aziz & Hafez, 2013; Bataglin et al., 2021). In general, lean construction tools are intended to improve the delivery systems and processes by minimizing wastes, increasing productivity and health and safety and overall, achieving client's requirements (Ansah et al., 2016). In essence, it will lead to better delivery processes and value-added systems through the removal of wastes; transportation, overproduction, inappropriate processing, lead time, inventories, rework and unnecessary movements in construction processes, hence, improve project and financial performance of the industry (Arbulú & Zabelle, 2006). However, compared to other industries, lean tools are not so widely known, and their use is not so common (Shah & Ward, 2003).

Lean Simulation Game in Construction Industry

While many construction companies claim substantial productivity and profit gains when applying lean construction principles, it remains a challenge to teach these principles in a classroom. Lean construction emphasises collaborative processes and integrated delivery practices. Consequently, new teaching methods that nurture such values should form the basis of lean construction education. One of the proposed methods is 'hands-on team simulation games' which can be employed to replicate various real-life processes, projects, or systems for the purpose of teaching, analysing, and understanding (Arefazar & Rybkowski, 2022).

The reason for this is that theoretical knowledge learned in simulation games can be actively tested directly and is thus not only better remembered, but also allows the advantages of the methods learned to be recognized directly in a playful manner (Binninger et al., 2017). In this way, the transfer of lean principles to the construction industry can be made clear and engrained patterns of thought can be broken (Alves et al., 2022).

A simulation game supports teaching by mimicking miniature-controlled experiments of actual processes that create opportunities for an “aha moment” among participants. In the world of lean, simulations are used to illustrate lean principles and create buy-in among those who will be implementing lean (Rybkowski et al., 2020). These games facilitate learning about the consequences of decisions and strategies through visual representation of processes and metrics (Shannon et al., 2010). This offers experiential learning of Lean principles in error-friendly, dynamic learning environments. Simulation games foster physical actions for learning by doing, which converts knowledge into a skill through the medium of realism (Arefazar & Rybkowski, 2022). This middle ground between practice and theory is necessary in order to develop valid and reliable knowledge to support practitioners in organisational/business to devise solutions to problems (Biotto et al., 2022).

These simulation games offer an optimal playground for testing ideas on a small scale (Alves et al., 2022). A study conducted by Hamzeh et al. (2017) revealed that simulation games can be employed to facilitate classroom instruction, improve the learning experience, and increase understanding of the theory behind lean construction and its real-world applications among engineering students. These types of games playfully visualize and simulate real-world events or processes in an environment that resembles realistic work situations. They can bring important theoretical topics to life, providing ways to understand and practice essential educational issues (Barraza, 2011). The core merit of a simulation game is that it integrates characteristics of simulation (about a real-life situation, event, or activity) and games (players, rules, competition, and cooperation) to transfer the knowledge of technologies and theories among practitioners and students (Rusca et al. 2012).

Simulations have played a crucial role in lean construction by successfully demonstrating the practical implications of lean principles. For example, simulations such as the Lego® Airplane Game and Parade of Trades simulation are regularly played by the Lean Construction community to educate participants about the impacts of pull, batching, and variability (Ansah & Sorooshian, 2017).

In summary, simulation games have become one of the most important ways to teach lean concepts over the years. Academics, practitioners, and consultants use simulations to engage people and enhance the learning experience in an applied setting. Simulations help bridge the gap in conceptual understanding when paired with readings and cases that provide additional background to the implementation of lean in real construction projects.

Methodology

The research is based on a systematic literature review, which is a means of identifying, evaluating, and interpreting documents relevant to a specific research question (Lavallee et al., 2014). A systematic literature review contains three general stages composing from seven steps as shown in Figure 2. According to Michalski et al. (2022), the first stage consists of identifying the purpose of the study. As it was mentioned earlier the paper aims to summarize the lean construction principles used in simulation games as presented in the literature, and to indicate possible topics for further studies. Keywords are the critical part of the review and the selected initial keywords in this study to meet the research purpose were “lean construction” and “simulation games.”

In the second stage, the literature sample is identified. This phase consists of three consecutive steps: identifying databases, defining inclusion and exclusion criteria, and reviewing and analysing (Trane et al., 2023). The research was based on Science Direct, International Group of Lean Construction (IGLC), and scholar.google.com databases. In the stage of selection of publications, the key phrase of the search was "lean construction". The secondary phrase was "simulation games". The search was performed for article titles, abstracts, and keywords. The language was then restricted only to English with no time restrictions. The third step of conducting stage is followed by analytical activities such as frequency analysis and content analysis.

The final stage is the development of the research areas and research gaps to suggest recommendations for future research studies. A total of 26 publications were included in this review to be analysed. The results of this review generally identify gaps in the knowledge and can be used as a starting point for further research on a specific topic.

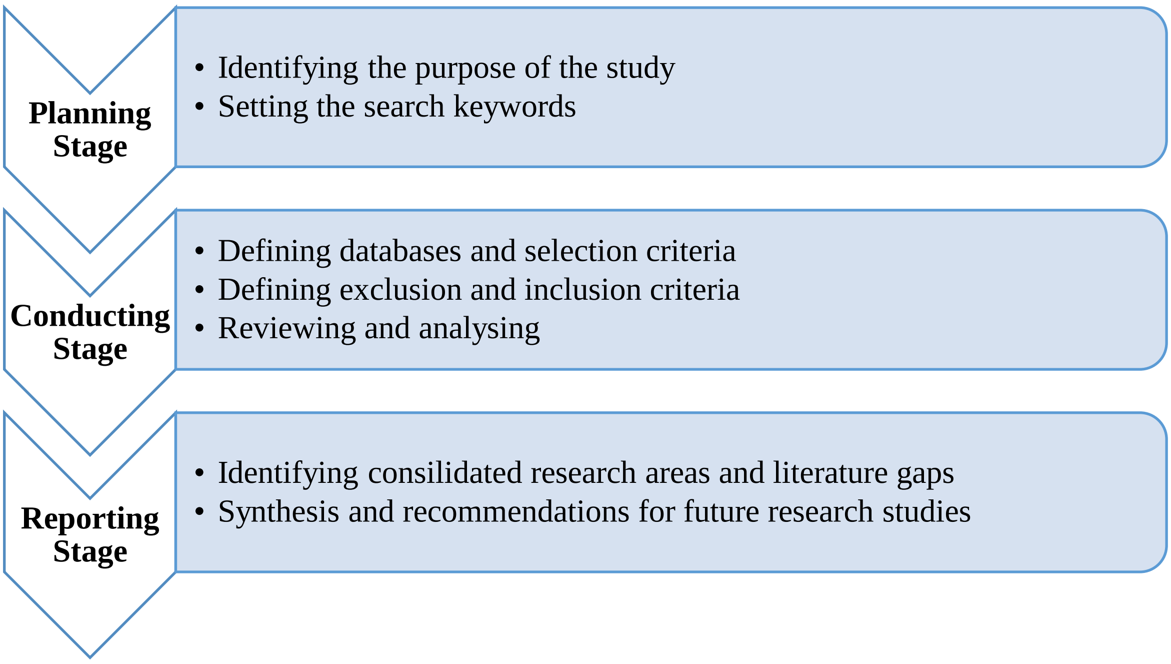

Figure 2: Steps of SLR carried out in the current study.

Results and Discussion

The researches’ analysis provided an overview about: (1) the distribution of studies over time; (2) the preferred research publishing types; (3) the type of the simulation game; and (4) The main lean principles that can be learned from reviewed simulation games. The results of analysing the publications were summarized in Table 1.

Figure 3 presents the number of the publications per year. The analysed papers appeared in 6 different journals and conference proceeding with 75% of those being published over the last 9 years (since 2014), but some going as far back as 1999. The largest number of papers appeared in the Annual Conference of IGLC as shown in Table 1.

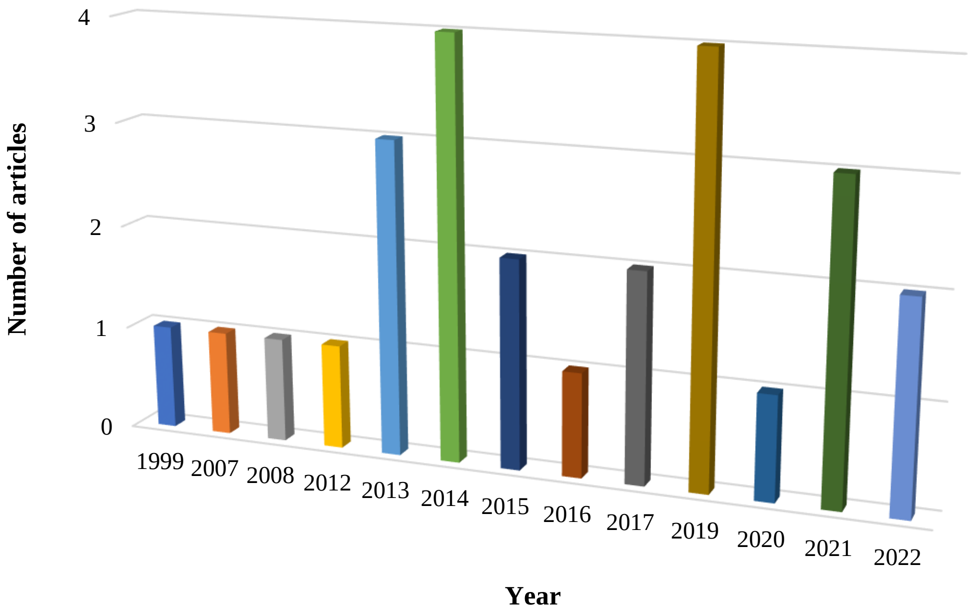

Figure 3: Number of publications per year.

While most simulations developed until 2019 relied mostly on in-person interaction (by hand), with some exceptions including those using computer simulations (Tommelein et al. (1999) parade game), during 2020 and beyond, academics and practitioners had to pivot and translate face-to-face simulations to online environments to continue teaching during the Covid-19 pandemic. The main lean principles that can be learned from reviewed simulation games are:

- Work-flow variability between trades
- One piece flow versus batching
- Pull versus push
- Demonstrates the main principles of 5S lean tool
- Multiskilling
- Target Value Design (TVD)
- Collaboration
- Value stream mapping (VSM)
- Last Planner System (LPS)
- Reliability of planning
- 4P (Philosophy: Long-Term Thinking)
- Communication
- Continuous improvement (Kaizen)
- Standardization,
- Analyse value-added, contributory and non-contributory activities

Table 1. Results of the SLR.

	Simulation game	Reference	Journal/Conference	Year	Simulation type	Lean principle/tool
1	Parade of Trades	Tommelein et al. (1999)	J. Constr. Eng. Manage.	1999	Computerized	Work-flow variability between trades
2	LEAPCON	Sacks et al. (2007)	J. Constr. Eng. Manage.	2007	Computerized	Pull flow Reducing batch size Multiskilling
3	Airplane Game	Rybkowski et al. (2008).	IGLC16	2008	Computerized	One piece flow versus batching Pull versus push
4	Oops Game	Howell and Liu (2012)	IGLC20	2012	Manual	Reliability of planning
5	Maroon-white Game	Smith and Rybkowski (2013)	IGLC21	2013	Manual	4P
6	Win As Much As You Can game	Tsao et al. (2013)	IGLC21	2013	Manual	Collaboration
7	5S Numbers Game	Tsao et al. (2013)	IGLC21	2013	Manual	5S lean tool
8	Villego	Warcup and Reeve (2014)	Lean Construction Journal	2014	Manual	LPS
9	A Last Planner-Driven Game	González et al. (2014)	IGLC22	2014	Manual	LPS
10	Collective Kaizen and Standardization Game	Rybkowski and Kahler (2014)	IGLC22	2014	Manual	Kaizen Standardization
11	Delta Design game	Pellicer and Ponz-Tienda (2014)	IGLC22	2014	Manual	Design management
12	LEBSCO	González et al. (2015)	Journal of Professional Issues in Engineering Education and Practice	2015	Manual	LPS
13	Make a Card game	Brioso (2015)	Procedia Engineering	2015	Manual	Kaizen Standardization The pull system Batch reduction Collaborative work

	Simulation game	Reference	Journal/Conference	Year	Simulation type	Lean principle/tool
14	Marshmallow TVD Simulation – Modified	Rybkowski et al. (2016)	IGLC24	2016	Manual	TVD (use of lean principles in design to achieve targets)
15	House of Cards	Pollesch et al. 2017	IGLC25	2017	Manual	5S lean tool
16	The Silent Squares Game	Hamzeh et al. (2017)	European Journal of Engineering Education	2017	Manual	Teamwork
17	TVD Simulation	Musa et al. (2019)	IGLC27	2019	Computerized	TVD
18	Target Value Design simulation	Devkar et al. (2019)	IGLC17	2019	Manual	TVD
19	Broken Square Game	Herrera et al. (2019)	Sustainability	2019	Manual	Communication Systemic thinking in work processes
20	Work Sampling Game	Herrera et al. (2019)	Sustainability	2019	Manual	Analyze value-added, contributory and non-contributory activities
21	Lean Simulation Game	Yaw et al. (2020)	IGLC28	2020	Manual	Multi-skilling Collaboration through Integrated Project Delivery
22	Virtual Parade Game	Biotto et al. (2021)	IGLC29	2021	Computerized	Teach the effects of variability in construction workflows
23	Simulation Game on Waste Elimination	Bhatnagar and Devkar (2021)	IGLC29	2021	Manual	5s lean tool Pull planning Kanban
24	5S Puzzle game	Obulam and Rybkowski (2021)	IGLC29	2021	Computerized	5S lean tool
25	The Silo Game	Alves (2022)	IGLC30	2022	Manual (online)	TVD Collaboration
26	VSM simulation	Arefazar and Rybkowski (2022)	IGLC30	2022	Computerized	VSM

Conclusion

Since the first adaption of lean management to the construction sector, numerous principals, methods and tools have been successfully adapted, developed and implemented. However, Lean Construction is often only partially or incorrectly applied. A basic cause is that site management and workers are not familiar with Lean Construction. Therefore, many researchers developed different lean simulation games to simplify the concept of lean construction. This paper by using a systematic literature review summarized the main lean concepts learned from different lean simulation games.

Current methods for teaching lean include hands-on projects and simulation games. Despite of many studies related to lean simulation games there is still significant limitations in this area. One of the most crucial issues is to use a digital learning platform that teaches the concept of lean construction using an active, hands-on serious gaming environment involving multiple players simultaneously in virtual reality. Moreover, a successful implementation of lean depends not only on the understanding of the individual principles, but also realizing the whole system philosophy.

References

Alves, S., Melzner, J., & Hollermann, S. (2022). Lean simulation game with BIM-based progress monitoring for takt control. *Proceedings of 30th Annual Conference of the International Group for Lean Construction,* pp. 307-317, Canada.

Alves, T. C. L. (2022). The Silo Game: a simulation on interdisciplinary collaboration. *Proceedings of 30th Annual Conference of the International Group for Lean Construction,* pp. 1052-1063, Canada.

Ansah, R. H., & Sorooshian, S. (2017). Effect of lean tools to control external environment risks of construction projects. *Sustainable Cities and Society*, *32*, 348-356.

Ansah, R. H., Sorooshian, S., & Mustafa, S. B. (2016). Lean construction: an effective approach for project management. *ARPN Journal of Engineering and Applied Sciences*, *11*(3), 1607-1612.

Arbulu, R., & Zabelle, T. (2006). Implementing lean in construction: how to succeed. *Proceedings of 14th Annual Conference of the International Group for Lean Construction,* pp. 553-565, Chile.

Arefazar, Y., & Rybkowski, Z. K. (2022). Developing & testing a value stream map simulation: helping the construction industry learn to see. *Proceedings of 30th Annual Conference of the International Group for Lean Construction,* pp. 342-353, Canada.

Aziz, R. F., & Hafez, S. M. (2013). Applying lean thinking in construction and performance improvement. *Alexandria Engineering Journal*, *52*(4), 679-695.

Bajjou, M. S., Chafi, A., & En-Nadi, A. (2017). The potential effectiveness of lean construction tools in promoting safety on construction sites. *International Journal of Engineering Research in Africa*, *33*, 179-193.

Ballard, G., & Howell, G. A. (2003). Competing construction management paradigms. *Proceedings of Construction Research Congress: Wind of Change: Integration and Innovation,* pp. 1-8.

Barraza, G. A. (2011). Probabilistic estimation and allocation of project time contingency. *Journal of Construction Engineering and Management, 137*(4), 259-265.

Bataglin, F. S., Viana, D. D., Coelho, R. V., Tommelein, I. D., & Formoso, C. T. (2021). Buffer types and methods of deployment in construction. *Proceedings of 29th Annual Conference of the International Group for Lean Construction, Peru*.

Bhatnagar, S., & Devkar, G. (2021). Development and testing of a simulation game on waste elimination using lean practices. *Proceedings of 29th Annual Conference of the International Group for Lean Construction, Peru*.

Bhatnagar, S., Jacob, G., Devkar, G., Rybkowski, Z. K., Arefazar, Y., & Obulam, R. (2023). A systematic review of lean simulation games in the construction industry. *Architectural Engineering and Design Management*, *19*(6), 701-719.

Binninger, M., Dlouhy, J., Oprach, S., & Haghsheno, S. (2017). Learning simulation game for takt planning and takt control. *Proceedings of 25th Annual Conference of the International Group for Lean Construction, Greece.*

Biotto, C. N., Herrera, R. F., Salazar, L. A., Pérez, C. T., Luna, R. M., Rodrigheri, P. M., & Serra, S. M. (2021). Virtual parade game for lean teaching and learning in students from Brazil and Chile. *Proceedings of 29th Annual Conference of the International Group for Lean Construction, Peru.*

Biotto, C., Kagioglou, M., Koskela, L., Tzortzopoulos, P., & Serra, S. (2022). Project pull planning based on location: from construction to design. *Proceedings of 30th Annual Conference of the International Group for Lean Construction,* pp. 599-610, Canada.

Brioso, X. (2015). Teaching lean construction: Pontifical Catholic University of Peru training course in lean project & construction management. *Procedia Engineering, 123,* 85-93.

Chuquín, F., Chuquín, C., & Saire, R. (2021). Lean and BIM interaction in a high rise building. *Proceedings of 29th Annual Conference of the International Group for Lean Construction,* pp. 136-144, *Peru*.

Cisterna, D., Hergl, M., Oprach, S., & Haghsheno, S. (2021). Digitalization of lean learning simulations: Teaching lean principles and last planner system. *Proceedings of 29th Annual Conference of the International Group for Lean Construction,* pp. 279-288, *Peru*.

Devkar, G., Trivedi, J., & Pandit, D. (2018). Teaching choosing by advantages: learnings & challenges. *Proceedings of 26th Annual Conference of the International Group for Lean Construction,* pp. 1385-1394, India.

Dixit, S., Mandal, S. N., Sawhney, A., & Singh, S. (2017). Area of linkage between lean construction and sustainability in Indian construction industry. *International Journal of Civil Engineering and Technology*, *8*(8).

González, V. A., Orozco, F., Senior, B., Ingle, J., Forcael, E., & Alarcón, L. F. (2015). LEBSCO: lean-based simulation game for construction management classrooms. *Journal of Professional Issues in Engineering Education and Practice*, *141*(4), 04015002.

González, V. A., Senior, B., Orozco, F., Alarcon, L. F., Ingle, J., & Best, A. (2014). Simulating lean production principles in construction: a Last Planner-driven game. *Proceedings of 22nd Annual Conference of the International Group for Lean Construction*, pp. 1221-1232, Norway.

Hamzeh, F., Theokaris, C., Rouhana, C., & Abbas, Y. (2017). Application of hands-on simulation games to improve classroom experience. *European Journal of Engineering Education*, *42*(5), 471-481.

Herrera, R. F., Sanz, M. A., Montalbán-Domingo, L., García-Segura, T., & Pellicer, E. (2019). Impact of game-based learning on understanding lean construction principles. *Sustainability*, *11*(19), 5294.

Holweg, M. (2007). The genealogy of lean production. *Journal of Operations Management*, *25*(2), 420-437.

Howell, G., & Liu, M. (2012). The OOPS game: how much planning is enough? *Proceedimngs of 20th Annual Conference of the International Group for Lean Construction,* Arlington.

Kenley, R. (2005). Dispelling the complexity myth: founding lean construction on location-based planning. *Proceedings of 13th Annual Conference of the International Group for Lean Construction, Australia*.

Koskela, L. (1992). Application of the new production philosophy to construction. *Stanford University*, *72*, 39.

Lavallée, M., Robillard, P. N., & Mirsalari, R. (2013). Performing systematic literature reviews with novices: an iterative approach. *IEEE Transactions on Education*, *57*(3), 175-181.

Marhani, M. A., Jaapar, A., & Bari, N. A. A. (2012). Lean construction: towards enhancing sustainable construction in Malaysia. *Procedia-Social and Behavioral Sciences*, *68*, 87-98.

Marhani, M. A., Jaapar, A., Bari, N. A. A., & Zawawi, M. (2013). Sustainability through lean construction approach: a literature review. *Procedia-Social and Behavioral Sciences*, *101*, 90-99.

Michalski, A., Głodziński, E., & Böde, K. (2022). Lean construction management techniques and BIM technology–systematic literature review. *Procedia Computer Science*, *196*, 1036-1043.

Musa, M., Pasquire, C., & Hurst, A. (2019, July). Using TVD simulation to improve collaboration. *Proceedings of 27th Annual Conference of the International Group for Lean Construction*, Ireland.

Nahmens, I., & Mullens, M. A. (2011). Lean homebuilding: lessons learned from a precast concrete panelizer. *Journal of Architectural Engineering*, *17*(4), 155-161.

Obulam, R., & Rybkowski, Z. K. (2021). Development and testing of the 5S puzzle game. *Proceedings of 29th Annual Conference of the International Group for Lean Construction,* pp. 309-319, Peru.

Pellicer, E., & Ponz-Tienda, J. L. (2014). Teaching and learning lean construction in Spain: a pioneer experience. *Proceedings of 22nd Annual Conference of the International Group for Lean Construction,* pp. 23-27, Norway.

Pollesch, P., Rovinsky, A., Alvarado, R., & Da Alves, T. C. L. (2017). House of cards–a simulation of lean construction principles. *Proceedings of 25th Annual Conference of the International Group for Lean Construction,* pp. 9-12, Greece.

Rusca, M., Heun, J., & Schwartz, K. (2012). Water management simulation games and the construction of knowledge. *Hydrology and Earth System Sciences*, *16*(8), 2749-2757.

Rybkowski, Z. K., & Kahler, D. L. (2014). Collective kaizen and standardization: the development and testing of a new lean simulation. *Proceedings of 22nd Annual Conference for the International Group for Lean Construction,* pp. 25-27, Norway.

Rybkowski, Z. K., Forbes, L. H., & Tsao, C. C. (2020). The evolution of lean construction education at US-based universities. In *Lean construction* (pp. 387-407). Routledge.

Rybkowski, Z. K., Munankami, M., Shepley, M. M., & Fernández-Solis, J. L. (2016). Development and testing of a lean simulation to illustrate key principles of target value design: a first run study. *Proceedings of 24th Annual Conference of the International Group for Lean Construction,* USA.

Rybkowski, Z. K., Wong, J. M., Ballard, G., & Tommelein, I. D. (2008). Using controlled experiments to calibrate computer models: the Airplane Game as a lean simulation exercise. *Proceedings of 16th Annual Conference of the International Group for Lean Construction,* UK.

Rybkowski, Z., Forbes, L., & Tsao, C. (2018). The evolution of lean construction education (Part 1 of 2): at US-based universities. *Proceedings of 26th Annual Conference of the International Group for Lean Construction,* India.

Sacks, R., Esquenazi, A., & Goldin, M. (2007). LEAPCON: simulation of lean construction of high-rise apartment buildings. *Journal of Construction Engineering and Management*, *133*(7), 529-539.

Shah, R., & Ward, P. T. (2003). Lean manufacturing: context, practice bundles, and performance. *Journal of Operations Management, 21*(2), 129-149.

Shannon, P. W., Krumwiede, K. R., & Street, J. N. (2010). Using simulation to explore lean manufacturing implementation strategies. *Journal of Management Education, 34*(2), 280-302.

Shaqour, E. N. (2022). The impact of adopting lean construction in Egypt: level of knowledge, application, and benefits. *Ain Shams Engineering Journal*, *13*(2), 101551.

Smith, J. P., & Rybkowski, Z. K. (2013). The Maroon and White Game: a simulation of trust and long-term gains and losses. *Proceedings of 21th Annual Conference of the International Group for Lean Construction,* Brazil.

Sundar, R., Balaji, A. N., & Kumar, R. S. (2014). A review on lean manufacturing implementation techniques. *Procedia Engineering*, *97*, 1875-1885.

Tommelein, I. D., Riley, D. R., & Howell, G. A. (1999). Parade game: impact of work flow variability on trade performance. *Journal of Construction Engineering and Management*, *125*(5), 304-310.

Trane, M., Marelli, L., Siragusa, A., Pollo, R., & Lombardi, P. (2023). Progress by research to achieve the sustainable development goals in the EU: a systematic literature review. *Sustainability*, *15*(9), 7055.

Tsao, C. C. Y., Azambuja, M., Hamzeh, F., Menches, C., & Rybkowski, Z. K. (2013). Teaching lean construction: perspectives on theory and practice. *Proceedings of 21th Annual Conference of the International Group for Lean Construction*, pp. 977-986, Brazil.

Ulewicz, R., & Ulewicz, M. (2020). Problems in the implementation of the lean concept in the construction industries. *Proceedings of CEE 2019: Advances in Resource-Saving Technologies and Materials in Civil and Environmental Engineering*, pp. 495-500.

Villego (2016). *Get hands-on Last Planner® experience with the Villego® Last Planner® simulation*. https://www.villego.com/

Von Heyl, J. (2015). Lean simulation in road construction: teaching of basic lean principals. *Proceedings of 23rd Annual Conference of the International Group for Lean Construction*, pp. 403-412, Australia.

Warcup, R., & Reeve, E. (2014). Using the Villego® simulation to teach the Last Planner® system. *Lean Construction Journal*.

Womack, J. P., & Jones, D. T. (1997). Lean thinking—banish waste and create wealth in your corporation. *Journal of the Operational Research Society*, *48*(11), 1148-1148.

Yaw, M. W., Rybkowski, Z., & Jeong, H. D. (2020). Reducing handoffs between sequential trades: a simulation. *Proceedings of 28th Annual Conference of the International Group for Lean Construction, USA.*

Zhang, L., & Chen, X. (2016). Role of lean tools in supporting knowledge creation and performance in lean construction. *Procedia Engineering*, *145*, 1267-1274.

Investigating Scenarios and Programs Utilized in Serious Game Based Applications for Engineering Education

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Abstract

The use of serious games in primary, middle, and high school education has been progressively increasing across various disciplines, ranging from Science, Technology, Engineering, and Mathematics (STEM) to social sciences. In recent years, propelled by technological advancements and widespread adoption of digital games, their use has become prevalent in university education. Construction engineering education aims to equip students with skills in planning, designing, and managing complex projects. In this context, serious games are believed to contribute to students' ability to translate theoretical knowledge into practical applications and to enhance their problem-solving skills. Effectively harnessing the potential of serious games necessitates their meticulous design with well-constructed scenarios and realistic visual quality. These elements can facilitate students' effective engagement in the process of translating theoretical knowledge into practical applications and problem-solving. Consequently, this study comprehensively investigated serious game scenarios developed for engineering education, particularly those adaptable to construction engineering, along with the programs employed in their implementation. The findings of this study are anticipated to aid in comprehending the potential contributions of serious games to construction engineering education.

Keywords: *digital game programs, engineering education, serious game, virtual reality.*

Introduction

Young people growing up immersed in technology (Generation Z) often find it challenging to adapt to educational programs that rely on traditional materials and techniques. This generation is focused on direct access to information. Consequently, they prefer accessing knowledge through web-based platforms, computers, smartphones, tablets, and similar means, rather than in conventional library settings. Educational resources enhanced with real-life imagery, simulations, animations, and interactive presentations have been shown to offer significant benefits in teaching (Bikçe et al., 2011), as evidenced through surveys, observations, and experiments. In recent years, along with videos designed to support education, virtual reality based educational materials, which leverage the latest technological advancements, have been developed to facilitate self-guided learning, leading to improved learning outcomes among students (Vergara et al., 2017).

Although the creation of virtual reality applications involves challenging and labor-intensive processes, which has slowed their adoption across broader society, the continuous advancement in technology has made these applications increasingly popular, leading to the development of various field-specific virtual reality applications and simulators. The integration of virtual reality into education has expanded students' potential for accessing educational resources (Balak, 2019; Kılıç, 2020). According to Clark (2006), virtual reality makes learning more engaging and enjoyable, thereby reducing education costs and increasing motivation and attention. It also allows users to experience scenarios that are impossible to explore in the real world. For example, it can enable exploration of planets like Mars, travel inside the human body, conduct underwater explorations, or view the interiors of caves. Additionally, virtual reality facilitates educational approaches that allow users to visit tiny molecules, experience distant or historical sites, among other things (Piovesan et al., 2012). Foreman et al. (2003) noted that the sensory and interactive nature of virtual reality has made it popular among researchers in education, rehabilitation, and cognitive neuroscience. The researchers explained that one reason for this popularity is that virtual reality environments offer a more 'controllable' world compared to the real one.

Another technological approach used in education is serious-based digital games. Serious games refer to any kind of game specifically designed to introduce players to a concept or to serve a dedicated educational purpose. The advantages of game-based learning in education are gaining increasing academic interest. Research indicates that game-based learning enhances student motivation. For example, the study by Jing et al. (2023) shows that games promote intrinsic motivation, leading to greater student engagement in the learning process. Similarly, Bazargani et al. (2021) found that game-based learning improves problem-solving and critical thinking skills. Additionally, Sena and Stochon (2023) noted that games increase information retention and comprehension levels. Finally, the study by Franco et al. (2020) indicates that game-based learning leads to higher levels of participation and interaction among students. These academic studies support the idea that game-based learning is a valuable tool in educational settings.

The combined use of virtual reality (VR) and digital games can lead to deeper learning experiences for students, promoting increased interaction and engagement, providing risk-free experiential learning opportunities, and fostering collaborative learning. Investigating the effects of using these two technological approaches together in the literature is crucial for educators and researchers to identify best practices and integrate them into classroom settings. Research into the application of technologies like virtual reality and digital games in education can offer valuable insights into enhancing learning outcomes and enabling students to learn more effectively. Furthermore, understanding the potential disadvantages and limitations of these technologies can help educators use them appropriately. Therefore, exploring the impact of the combination of VR and digital games in education is a critical step toward shaping future educational strategies.

The purpose of this study is to comprehensively examine serious game scenarios developed for engineering education, particularly those adapted for civil engineering, and the software programs used to implement them. The findings from this study are expected to contribute to a better understanding of the potential benefits of serious games in civil engineering education.

Method

A search was conducted in the 'Scopus' database to investigate virtual reality-based serious game scenarios and the software programs used in game development. The keywords 'virtual reality', 'game', and 'education' were used for scanning titles and abstracts. This search yielded a total of 2,897 articles. To focus on more recent studies, the research was limited to publications from the last five years. With this restriction, the total number of publications was reduced to 1,162. To ensure relevance to the study topic, the subject area was set to 'Engineering', which further reduced the number of articles to 425. From these 425 publications, book chapters, conference papers, and reviews were excluded, leaving only research articles in the scope of analysis. This step resulted in 124 articles. By focusing solely on open-access publications, the number was reduced to 83 articles. The keywords 'virtual reality', 'e-learning', 'education', 'students', 'engineering education', and 'serious games' were used to refine the selection, bringing the count to 62 articles. Further examination removed those that used mixed or augmented reality instead of virtual reality, lacked game scenarios, or did not produce actual games, resulting in 25 articles. The subjects of the virtual reality-based games in these 25 articles, as well as the software used to create them, were examined. Finally, articles that focused on topics like medical education, sports education, or language education were excluded, leaving 14 articles for in-depth analysis. Research methodology is given Figure 1.

Serious Games Developed in the Field of Virtual Reality

Mayor and Lopez-Fernandez (2021) developed a virtual reality-based serious game called Scrum VR, designed for mobile devices with low graphical quality, using Unity game engine version 2019.4.13f1. The game focuses on software engineering. Unreal Engine was not chosen due to its higher graphical requirements and the potentially large file size of Unreal-based games. The primary goal of this program is to create an engaging and educational virtual reality experience for users, focusing on teaching agile methodologies in software engineering through Scrum. The application aims to simulate the early days of working in a software development team that uses Scrum methodology. Agile project management is an iterative approach to software development, emphasizing collaboration, rapid software releases, and customer feedback. Scrum is one of the successful agile project management techniques, used to handle complex software processes. It divides tasks into smaller segments, allowing for steady progress and adaptability to changing conditions. By breaking down tasks, time is saved, largely due to the high level of communication and teamwork inherent in Scrum. Constant communication reduces the likelihood of errors and saves time. Two evaluation processes conducted with university instructors and students indicated that the developed video game meets its intended objectives and shows promise.

Paliling et al. (2022) developed a virtual reality-based serious game related to disaster management using the Unity game engine. This game was designed to raise public awareness about flood disasters and to teach what to do in case of an emergency. The game consists of levels that include tasks such as rescuing valuable items and reaching designated locations. The results of tests and surveys indicated that the game was functional and effective in improving responses to flood disasters. Figures related to the game are provided in Figure 1.

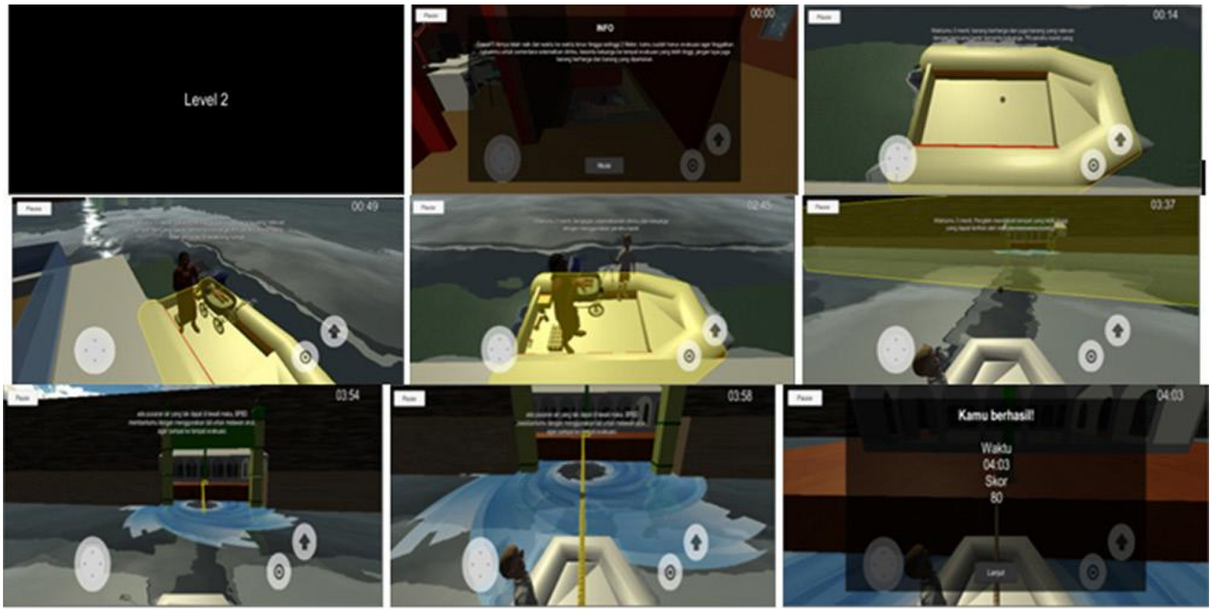

Figure 1: Escape from the flood (Paliling et al., 2022).

Franco et al. (2020) developed three different virtual reality-based serious games using Unity game engine and Revia® programming technology. These games include Python scripts that allow users to change certain features through user-friendly interfaces. The games offer unique educational experiences, featuring interactions with battery components, driving electric vehicles, and running 3D structures in a virtual smart grid. To help students better understand the topics, the games include various tasks and instructions. Different audiences, including students, academics, and the general public, interacted with these VR-based serious games and provided feedback. The results were generally positive in terms of student engagement, understanding of complex concepts, and interdisciplinary collaboration. This suggests that virtual reality-based teaching methods might be more effective than traditional approaches for subjects like materials science, batteries, and mathematical modeling. Visual representations of the games are provided in Figure 2.

Figure 2: Nanoviewer VR (Franco et al., 2020).

Paszkiewicz et al. (2021) developed a virtual reality-based serious game called ELIAKI VR using the Unreal Engine game engine and Autodesk 3ds Max software. This game includes various tasks and instructions to teach students the logic, structure, and applications of digital circuits. Students engage in tasks within a virtual environment where they build logic circuits using various logic gates, such as AND, NAND, and OR, as part of their learning process. To evaluate the games, simulated circuit exercises and error detection methods were employed. This approach allowed students to independently correct the problems they encountered when they made mistakes. In an experimental study involving 40 students, the results indicated positive outcomes regarding students' engagement in learning digital circuits through a virtual reality-based serious game. Visual representations related to the game are provided in Figure 3.

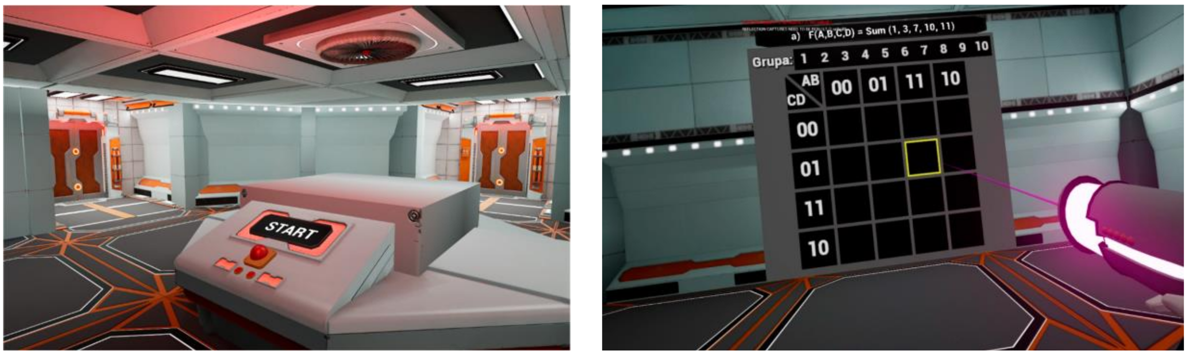

Figure 3: ELIAKI VR (Paszkiewicz et al., 2021).

de Sena and Stachoň (2023) aimed to teach students certain topics in geography class by adding tasks and scenarios related to global climate zones to the game Minecraft. Learning activities designed for geography education in Minecraft include a map room showing climate zones, an interactive player panel, and NPCs that guide players throughout the tasks. Players explore climate zones, collect plant samples, answer multiple-choice questions, and receive feedback through in-game sounds. To evaluate the game mechanics and player engagement, two game testing sessions were conducted with high school and university students. The study concluded that Minecraft, with its ability to allow players to create and explore virtual worlds, is a versatile tool for creating educational content.

Bazargani et al. (2021) developed a virtual reality-based serious game called IVREG using Unity3D and UnityXR game engines to teach students about topological relationships in Geographic Information Systems. The instructional design focuses on balancing entertainment with learning by integrating everyday activities, inquiry-based learning, problem-based learning, and teaching through presentations. The study procedure includes the introduction of terms, completion of pre-tests, playing the game, exploring the room, answering questions, and using clues to escape. The game mechanics involve interactions such as grabbing objects, painting, and solving topology-related questions to escape from the room. In an experimental study involving 37 students, it was found that IVREG's learning environment and components were suitable and effective in schools, especially for learning topics related to geographic-spatial relationships.

Anifowose et al. (2023) used the Unity game engine to create a virtual reality-based serious game model called EnergySIM, focusing on the design of energy-efficient buildings. Autodesk Revit, SketchUp, and 3DMax were utilized to create the game's three-dimensional materials. EnergySIM includes a solar clock scenario that demonstrates the sun's position throughout the year, along with responses from simulated thermal heatmaps of building exteriors for each of the four seasons (winter, summer, autumn, and spring). For indoor atmospheric temperature mapping, the game also provides four different pre-simulated material scenarios (single-pane glass, double-pane glass, concrete, and wood). The interaction methods allow users to visually assess different construction materials based on insulation capacity or resistance to heat flow (R-value). EnergySIM offers a hands-on, visually engaging learning experience aimed at enhancing knowledge retention and understanding.

Gervasi et al. (2023) used the Blender program to design 3D models and then integrated these models into the Unity game engine to develop a virtual reality platform aimed at introducing students to 3D objects. In a study involving 162 students, it was found that the virtual reality platform significantly contributed to students' learning of 3D objects.

Soto-Martin et al. (2020) developed a virtual reality-based platform using the Unity game engine and DStretch® software to teach architectural design of historical structures. This platform allows users to explore a cultural heritage site in real-time, observe architectural and artistic details, and interact with these elements. Figures related to game are shown in Figure 4.

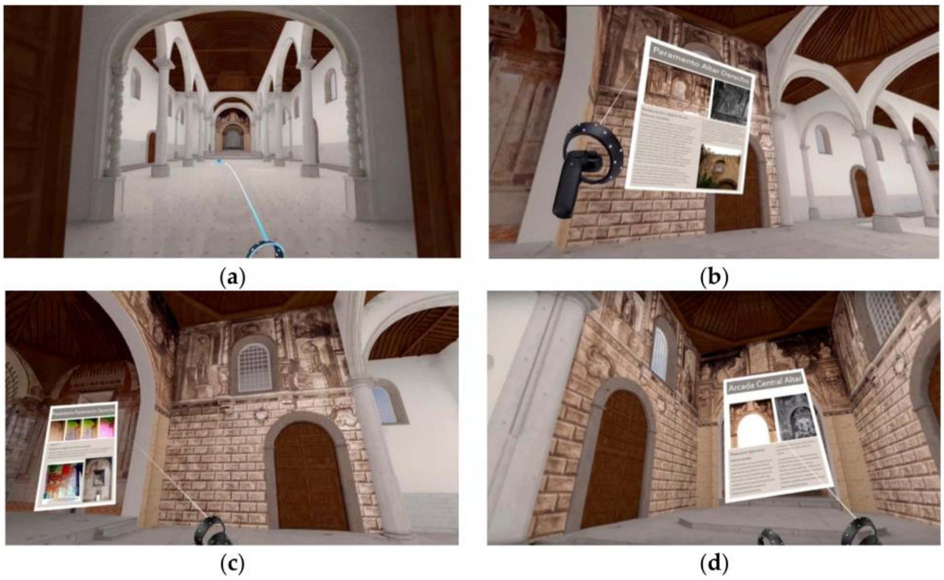

Figure 4: VR application related to historical buildings (Soto-Martin et al., 2020).

Gross et al. (2023) developed a virtual reality-based serious game using the Unreal Engine game engine to demonstrate changes in coastal vegetation and species distribution to students. The game contributes to geoscience education by visualizing how weather changes, wind, waves, pollution, and climate change impact the vegetation.

Khan et al. (2021) developed a serious game using the Unity game engine to provide traffic safety education to children and enable them to practice in simulated virtual reality environments. This game allows children to learn traffic rules in a virtual setting and practice these rules at home without being exposed to real-world risks. By doing so, the game aims to reduce traffic-related accidents involving children. To ensure the safety of the children, an additional control layer is included in the game to assess their skills. This allows for determining when a child meets specific criteria and scores, indicating that they are ready for real-world application. To demonstrate the effectiveness and robustness of the proposed system, four types of subjective activities were conducted on a group of ten students with average grades in their classes. The experimental results show that the proposed system has a positive impact on improving children's behavior when crossing the street. Figure 5 contains visuals related to the game.

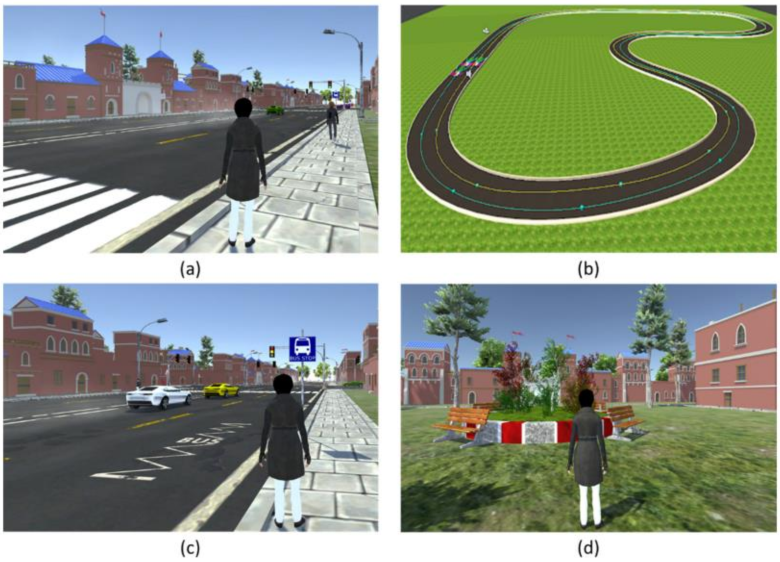

Figure 5: Road safety education (Khan et al., 2021).

Shi et al. (2023) presents the system development process of a collaborative simulation platform designed to study driving behavior with multiple participants. The objective of the study is to create an immersive and interactive environment where various driving scenarios can be simulated, and driver behaviors can be recorded and analyzed. The platform combines the Unity game engine with the VISSIM microscopic traffic simulator to create a hybrid simulation environment that leverages the strengths of both technologies. During the simulation experiments, a virtual reality massively multiplayer online (VRMMO) module was developed to capture the interactions among participants. Moreover, the external control devices of this collaborative simulation platform were calibrated using empirical data from the Controller Area Network (CAN-BUS) derived from real driving behaviors. The key contributions of this study include demonstrating the effectiveness of the Unity-VISSIM collaborative simulation platform for simulating interactive driver behaviors, and highlighting its potential applications in various research domains such as intelligent transportation systems, human factors, driver training, and traffic safety analysis. The platform can serve as a valuable tool for assessing the efficacy of collective intelligence-based countermeasures for traffic system improvements with relatively lower cost and risk. The Unity-VISSIM collaborative simulation platform provides a comprehensive approach to studying driving behavior by combining Unity and VISSIM, and offers realistic virtual environments for analyzing factors such as traffic density, weather conditions, and driver interactions.

O'Grady et al. (2021) have developed a new virtual reality (VR) approach using the Unity game engine to provide advanced learning and experience in the context of circular economy (CE) within the construction industry. This approach incorporates a prototype CE building designed by combining game design with a digital twin derived from building information modeling (BIM). The proposed VR environment offers a visual representation of materials and components that can be reintegrated into the supply chain at the end of their lifecycle, along with the extraction procedures and material sources. The aim of this approach is to provide a platform for building designers to visualize and implement strategies aligned with CE principles. Figures related to the game are provided in Figure 6.

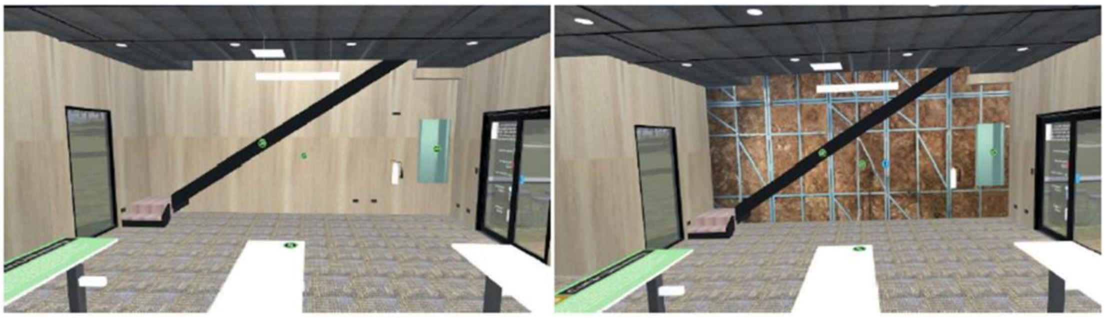

Figure 6: VR application related to circular economy (O'Grady et al., 2021).

De Fino et al. (2023) developed a virtual reality-based serious game prototype using the Unreal Engine game engine to help individuals develop responsive behaviors to slow-evolving or sudden disasters, thereby creating more resilient human-urban interactions. This prototype is designed for different hazard scenarios in urban open spaces and aims to promote interactions that enhance safety and sustainability. The article details the design and implementation of the prototype, considering functional features such as the virtual environment, interaction modes, learning outcomes, and narrative elements. The prototype is demonstrated through its informative content, which includes simulation-based analyses of surface temperatures, the size of falling debris, and response strategies for heatwaves and earthquakes. Additionally, it presents scenarios for safely guiding crowd movement. The ultimate goal of the prototype is to provide an adaptable and scalable tool for urban contexts, both to educate about critical disaster situations and to communicate mitigation strategies. This approach supports education and awareness efforts to address various disasters that might occur in urban settings. Figures related to the game prototype are provided in Figure 7.

Figure 7: VR game releated to disaster education (De Fino et al., 2023).

Results and Discussion

This study examines which platforms have been used to develop virtual reality-based serious games for engineering education over the past five years and what types of scenarios these games include. The research involves the analysis of 14 academic articles, uncovering virtual reality applications in fields such as software engineering, architecture, construction, disaster management, road safety, electrical-electronic engineering, and energy engineering. Of the 14 articles, three employed the Unreal game engine, 10 used Unity, and one involved modification within the Minecraft game. According to the findings, two of the games address disaster management: one deals with circular economy systems in construction, two focus on road safety, one showcases three-dimensional object representation, one explores architectural history, two are related to energy engineering, 3 pertain to climate and geography, and two are related to software engineering.

Comparisons with existing literature confirm that these results are consistent with those of previous research. For example, VR-based serious games can allow students to work on a virtual construction site where they can experience safety procedures and structural design (Yan et al., 2011; Häfner et al., 2013; Dinis et al., 2017; Wang et al., 2020; Soto-Martin et al., 2020; Fonseca et al., 2021; De Fino et al., 2023; Gervasi et al., 2023). Electrical engineering students can design and analyze circuits in a virtual laboratory, transforming theoretical knowledge into practical skills (Franco et al., 2020). These experiences offer students a safe environment in which to apply engineering principles and address potential issues. In addition, these games often require collaboration, which promotes teamwork and cooperation (Uz-Bilgin et al. 2020). In this way, students not only develop their technical skills but also get the opportunity to practice social skills, such as communication and teamwork.

Conclusions

The outcomes of this study indicate that virtual reality (VR)-based serious games are emerging as revolutionary pedagogical tools in engineering education. The results of the experimental studies in the reviewed articles suggest that VR technology offers students the opportunity to learn complex engineering concepts in an interactive and experiential manner. Unlike traditional classroom methods, VR-based serious games allow students to engage in real-world scenarios, providing opportunities to solve engineering problems, which in turn helps them to better understand abstract concepts in a more concrete way. Moreover, these games also promote critical thinking skills.

With ongoing advancements in VR technology, there is a strong likelihood that more sophisticated and effective educational experiences will emerge, fostering further transformation in engineering education. The evidence indicates that graduates who undergo training through VR-based serious games are likely to possess a more robust combination of theoretical knowledge and hands-on skills, making them better prepared for the demands of the modern workforce. In summary, VR-based serious games offer an intriguing avenue for enriching educational processes, facilitating an engaging, interactive, and collaborative learning environment. The present study highlights the role of VR in reshaping engineering education and suggests that sustained research and development in this domain are essential for unlocking the full potential of these technological tools.

Moreover, the analysis of the scenarios and software utilized in the recent articles examined in this study provides valuable insights that can guide future research efforts. This review illustrates how virtual reality-based serious games are being implemented in the field of education, along with the specific software and technologies that underpin these applications. As such, it serves as a robust reference point for academics who plan to undertake similar research in the future.

References

Anifowose, H., Alhazzaa, K., & Dixit, M. (2023). Energysim: techniques for advancing building energy education through immersive virtual reality (vr) simulation. *Journal of Information Technology in Construction*, *28*.

Balak, M., V., (2019). *Developing interactive three dimensional contents for use in technical drawing course and investigating the effect on learning process* [PhD thesis]. Harran University.

Bikçe, M., Deliktaş, B., Coşkun, H., & Türker H. T. (2011). Ab Cemlib projesi ile mühendislik mekaniği ders uygulamaları. *Proceedings of 2017 2nd Civil Engineering Education Symposium*, pp. 141-149, Turkey.

Clark, R. E. (1983). Reconsidering research on learning from media. *Rewiev of Educational Research, 53*, 445-459.

De Fino, M., Tavolare, R., Bernardini, G., Quagliarini, E., & Fatiguso, F. (2023). Boosting urban community resilience to multi-hazard scenarios in open spaces: a virtual reality–serious game training prototype for heat wave protection and earthquake response. *Sustainable Cities and Society*, *99*, 104847.

De Sena, Í. S., & Stachoň, Z. (2023). Designing learning activities in minecraft for formal education in geography. *International Journal of Emerging Technologies in Learning*, *18*(4), 32.

Dinis, F. M., Guimarães, A. S., Carvalho, B. R., & Martins, J. P. P. (2017). Virtual and augmented reality game-based applications to civil engineering education. *Proceedings of 2017 IEEE Global Engineering Education Conference*, pp. 1683-1688.

Fonseca, D., Cavalcanti, J., Peña, E., Valls, V., Sanchez-Sepúlveda, M., Moreira, F., & Redondo, E. (2021). Mixed assessment of virtual serious games applied in architectural and urban design education. *Sensors*, *21*(9), 3102.

Foreman, N., Stanton, D., Wilson, P., & Duffy, H. (2003). Spatial knowledge of a real school environment acquired from virtual or physical models by able-bodied children and children with disabilities. *Journal of Experimental Psychology: Applied*, *9*, 67-74.

Franco, A. A., Chotard, J. N., Loup-Escande, E., Yin, Y., Zhao, R., Rucci, A., & Lelong, R. (2020). Entering the augmented era: immersive and interactive virtual reality for battery education and research. *Batteries & Supercaps*, *3*(11), 1147-1164.

Gervasi, O., Perri, D., & Simonetti, M. (2023). Empowering knowledge with virtual and augmented reality. *IEEE Access*.

Gross, F., Petersen, L., Wallmeier, C., Barrett, R., Kwasnitschka, T., & Karstens, S. (2023). From coastal geomorphometry to virtual environments. *Frontiers in Marine Science*, *10*.

Häfner, P., Häfner, V., & Ovtcharova, J. (2013). Teaching methodology for virtual reality practical course in engineering education. *Procedia Computer Science*, *25*, 251-260.

Jing, Z., Wang, D., & Zhang, Y. (2023). The effect of virtual reality game teaching technology on students' immersion. *International Journal of Emerging Technologies in Learning*, *18*(8), 183.

Khan, N., Muhammad, K., Hussain, T., Nasir, M., Munsif, M., Imran, A. S., & Sajjad, M. (2021). An adaptive game-based learning strategy for children road safety education and practice in virtual space. *Sensors*, *21*(11), 3661.

Kılıç, T. (2020). *Suggestion of a model for the use of virtual reality technology in interior architecture education* [PhD thesis]. Mimar Sinan Güzel Sanatlar Üniversitesi.

Mayor, J., & López-Fernández, D. (2021). Scrum vr: virtual reality serious video game to learn scrum. *Applied Sciences*, *11*(19), 9015.

O'Grady, T. M., Brajkovich, N., Minunno, R., Chong, H. Y., & Morrison, G. M. (2021). Circular economy and virtual reality in advanced BIM-based prefabricated construction. *Energies*, *14*(13), 4065.

Paszkiewicz, A., Salach, M., Strzałka, D., Budzik, G., Nikodem, A., Wójcik, H., & Witek, M. (2021). VR education support system—a case study of digital circuits design. *Energies*, *15*(1), 277.

Piovesan, S. D., Passerino, L. M., & Pereira, A. S. (2012). Virtual reality as a tool in the education. *International Association for Development of the Information Society*, 295-298.

Safari Bazargani, J., Sadeghi-Niaraki, A., & Choi, S. M. (2021). Design, implementation, and evaluation of an immersive virtual reality-based educational game for learning topology relations at schools: a case study. *Sustainability*, *13*(23), 13066.

Shi, X., Yang, S., & Ye, Z. (2023). Development of a unity–VISSIM co-simulation platform to study interactive driving behavior. *Systems*, *11*(6), 269.

Soto-Martin, O., Fuentes-Porto, A., & Martin-Gutierrez, J. (2020). A digital reconstruction of a historical building and virtual reintegration of mural paintings to create an interactive and immersive experience in virtual reality. *Applied Sciences*, *10*(2), 597.

Uz-Bilgin, C., Thompson, M., & Anteneh, M. (2020). Exploring how role and background influence through analysis of spatial dialogue in collaborative problem-solving games. *Journal of Science Education and Technology*, *29*, 813-826.

Vergara, D., Rubio, M. P., & Lorenzo, M. (2017). New approach for the teaching of concrete compression tests in large groups of engineering students. *Journal of Professional Issues in Engineering Education and Practice*, *143*(2), 05016009.

Yan, W., Culp, C., & Graf, R. (2011). Integrating BIM and gaming for real-time interactive architectural visualization. *Automation in Construction*, *20*(4), 446-458.

Wang, R., Lowe, R., Newton, S., & Kocaturk, T. (2020). Task complexity and learning styles in situated virtual learning environments for construction higher education. *Automation in Construction*, *113*, 103148.

A Systematic Literature Review on Project and Construction Management Education

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Abstract

The aim of project and construction management education is to reinforce the managerial skills necessary for the implementation of a construction project, teach analysis and design knowledge, provide information about the construction process and the management of construction companies, and examine the economic, legal, social, and environmental impacts of construction projects to broaden perspectives. In this context, the learning outcomes of this education involve students gaining both theoretical and practical knowledge to develop managerial skills and prepare for the multidisciplinary working environment and dynamic construction site conditions required by the construction sector. However, the requirements of the era and the advancement of technology have led to changes in the expected qualities from project and construction management education. In the literature, there are various scientific studies focusing on different approaches to project management education. While most of these scientific studies are based on sample studies, only a few provide a systematic review of the existing body of knowledge. Within the scope of this study, a systematic literature review has been conducted on construction and project management education. The aim is to identify new boundaries of construction and project management education, determine the approaches developed over time, and classify them.

Keywords: *construction management, education, project management, systematic review.*

Introduction

Today, the importance of project and construction management has increased due to the combination of different disciplines in construction projects, the uniqueness of projects, and the growth of project volumes. The most important goal has become to deliver the highest quality work in limited time and cost (Taner & Parlak Biçer, 2021). Construction projects require advanced planning, a large workforce, a significant amount of time, and precise execution to achieve project objectives (Aliu et al., 2023).

The importance of proper management of complex construction projects and therefore the importance of project and construction management education is increasing both in Turkey and in the world. However, the insufficiency of scientific studies in this field is striking. In this context, within the scope of this study, a bibliometric analysis was conducted in the field of project and construction management education and the cumulative knowledge in this field was classified and boundaries were drawn. Thus, it is aimed to identify the ambiguous regions in the field of construction and project management education.

Project and Construction Management Education

The aim of construction management education is to provide knowledge about the management of the construction process and construction companies in relation to the analysis and design processes and to teach the economic, legal, social and environmental frameworks of construction projects. In this context, construction management education includes both theoretical and practical knowledge. Construction management education aims to provide managerial skills and prepare students for the multi-layered working environment and dynamic construction site conditions required by the construction industry (Birgönül et al., 2007).

Today, there are 208 universities in Turkey, including state and foundation universities (Higher Education Program Atlas, 2024). When the departments of universities are examined, it is seen that there is no separate department in the field of construction management and construction project management; these trainings are included in the education contents of civil engineering and architecture departments. In this context, it can be said that project and construction management is not seen as an independent field in Turkey. In many countries such as the United States, Italy, Germany, the United Kingdom, and Japan, project and construction management is seen as an independent profession and there are many undergraduate and graduate programs in this field (İnce & Topraklı, 2019).

Research Methodology

Bibliometrics is the analysis of scientific studies with the help of numerical analysis and statistics. Bibliometric methods use a quantitative approach to identify, evaluate, and track published research. Bibliometric analysis method is performed for performance analysis and science mapping purposes. Performance analysis shows the evaluation of research and publications of individuals and organizations. Science mapping aims to reveal the structure and dynamics of the scientific field (Zupic & Čater, 2015).

In order to use bibliometric methods in studies, data are obtained from databases such as Web of Science (WOS), Scopus or Dimension. Within the scope of the study, WOS database was preferred as the main source. The data obtained from these software bases are visualized with software programs such as Citespice, Vivo, Gephi, Histcite, Bibeexcel, Ucinet, Pajek, Vantage Point, Scimat, VOSviewer and used in studies (Karagöz & Şeref, 2019). Within the scope of the study, the VOSviewer program was used in the structuring of bibliometric networks due to its easy access and successful mapping of data analysis.

Results

Within the scope of the study, the keywords "construction management" and "project management" and "education" and "course" were searched in the WOS database. In this search, 276 scientific studies were found. The first study in this field was conducted in 1993. There were 3 scientific studies until 2000. The most studies in this field were conducted in

2015. After this date, there is a decrease in the number of scientific studies (Figure 1) (Web of Science, 2024).

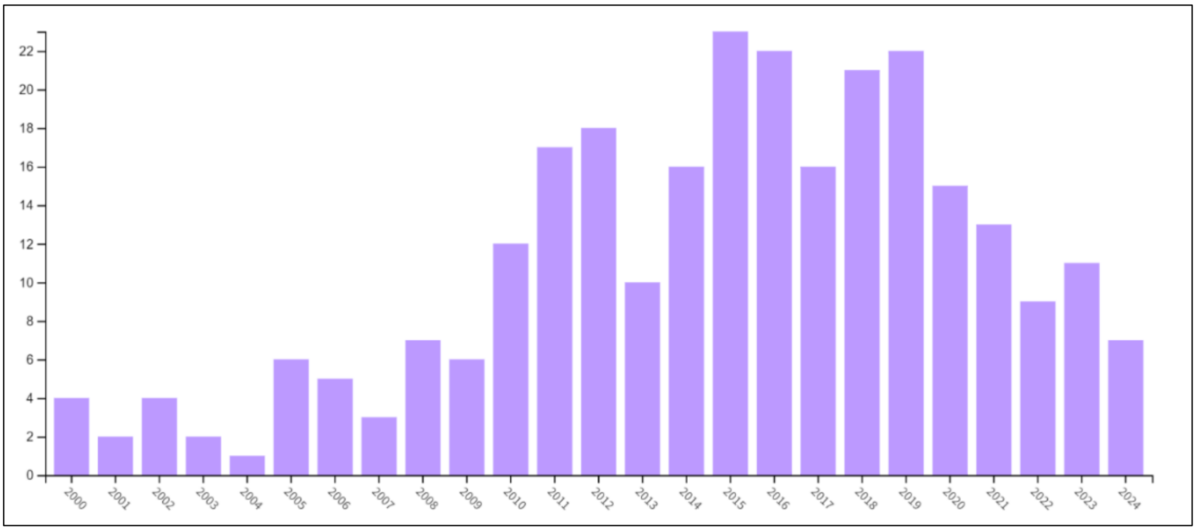

Figure 1: Time-dependent change in the number of scientific studies in the WOS database (Web of Science, 2024).

The data obtained from the WOS database were processed in the VOSviewer analysis program. As an application, an example of the analysis techniques frequently used in the field was made and interpreted. In this context, firstly, countries were analyzed in citation unit. Countries with at least 2 studies in the relevant field and 1 citation were accepted as the threshold. It was determined that scientific studies were published in 20 different countries in this field. It was observed that the most studies were conducted in the USA, China, England, Turkey, Scotland, and Australia, respectively (Figure 2). However, it was observed that there was no relationship between the studies conducted in Austria and the studies conducted in other countries, and that the focus of the studies was on America (Figure 3).

Country	Documents	Citations
usa	22	310
peoples r china	9	23
england	3	17
scotland	2	14
turkey	3	35
australia	2	28

Figure 2: Number of scientific studies and citations in countries in the relevant field.

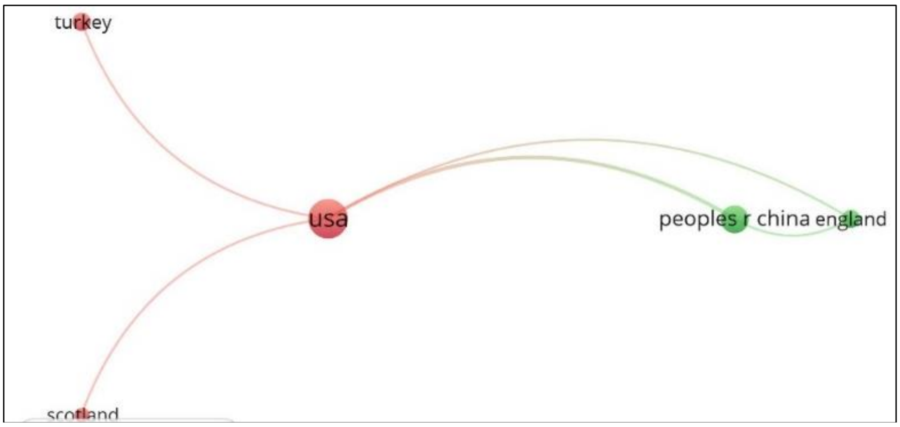

Figure 3: Relationship network of countries analyzed with VOSviewer.

Another analysis conducted within the scope of the research is the status of universities in the citation unit. In the analysis made with VOSviewer, it was determined that 71 different universities conducted studies in the relevant field. Studies that received at least 2 citations from scientific studies in these universities were accepted as threshold. California State University (79 citations), Philadelphia University (79 citations), and Virginia Tech (79 citations) are the most cited universities. From Turkey, Istanbul Technical University (18 citations) and Çukurova University (2 citations). The density relationship between these universities is visualized below (Figure 4).

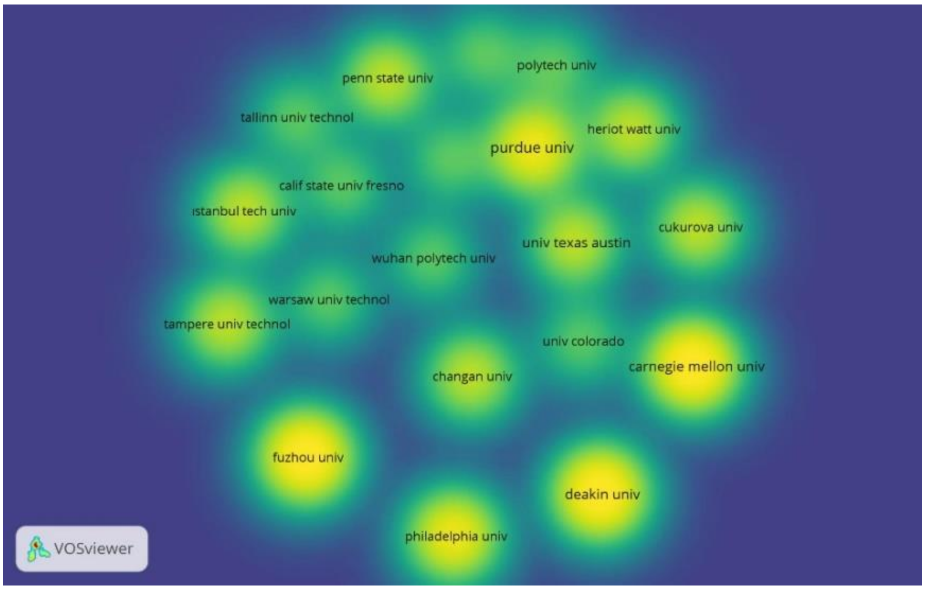

Figure 4: The relationship between citation density of universities.

In VOSviewer software, an analysis was made on the status of authors in the co-authorship unit. accordingly, it was determined that 136 authors had at least 1 study in the relevant field. among these authors, authors with at least 5 citations were accepted as threshold. There are 46 authors with at least 5 citations. The relationship between them is mapped below (Figure 5).

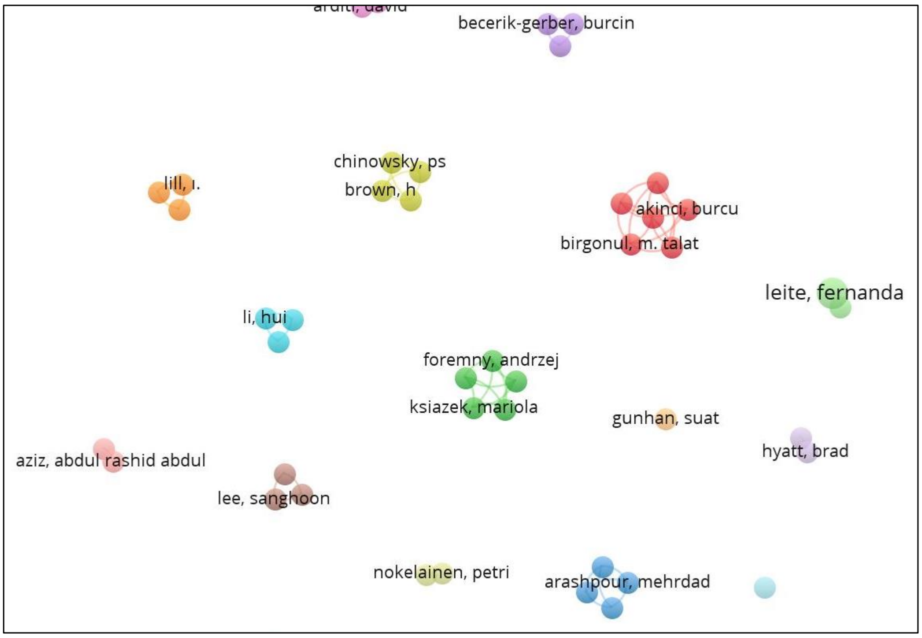

Figure 5: Relationship of authors in the related field.

In the research, the keywords in scientific studies were analyzed. A total of 158 keywords were found in the research. Words with at least 2 of them in common were accepted as threshold. Accordingly, it was determined that the keywords “construction management”, “engineering education”, “building information model”, “construction education”, “education”, “project management”, “construction management education” were found the most in the research respectively (Figure 6).

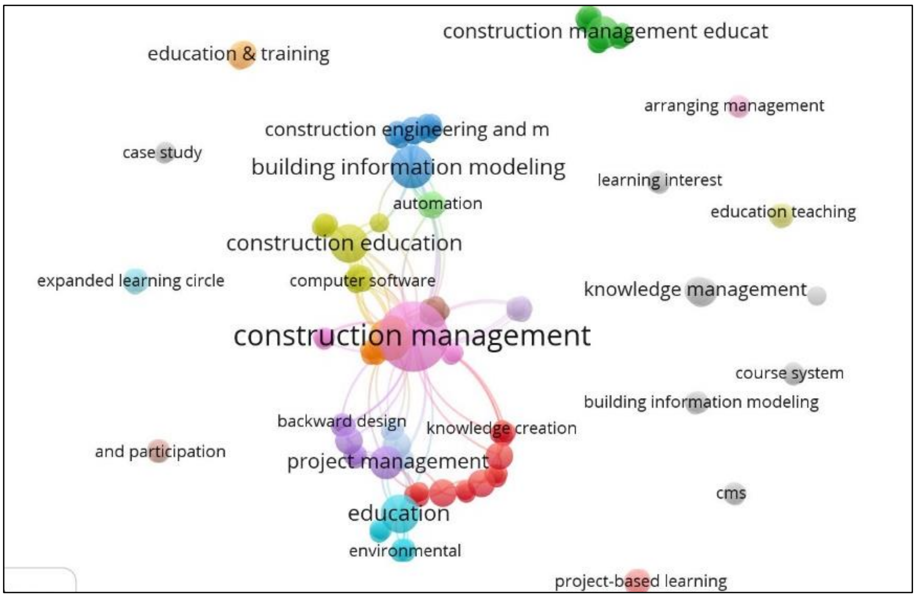

Figure 6: Relationship of keywords found in the analysis.

The transformation of the keywords identified in the study over time was also analyzed. Accordingly, there are studies conducted between 2010-2015 with the keywords “construction management”, “e-learning”, “cognitive theory”, “education”, “developing countries”, “education teaching”, “expanded learning circle”, “environmental”. Between 2015-2020, studies were conducted with the keywords “building information modeling”, “backward design”, “construction engineering”, “course system”, “innovation”, “computer software”, “construction education” and “project-based learning”. Nowadays, scientific publications have been made with the keywords “automation”, “AEC-FM education”, “agglomerative hierarchical cluster” (Figure 7).

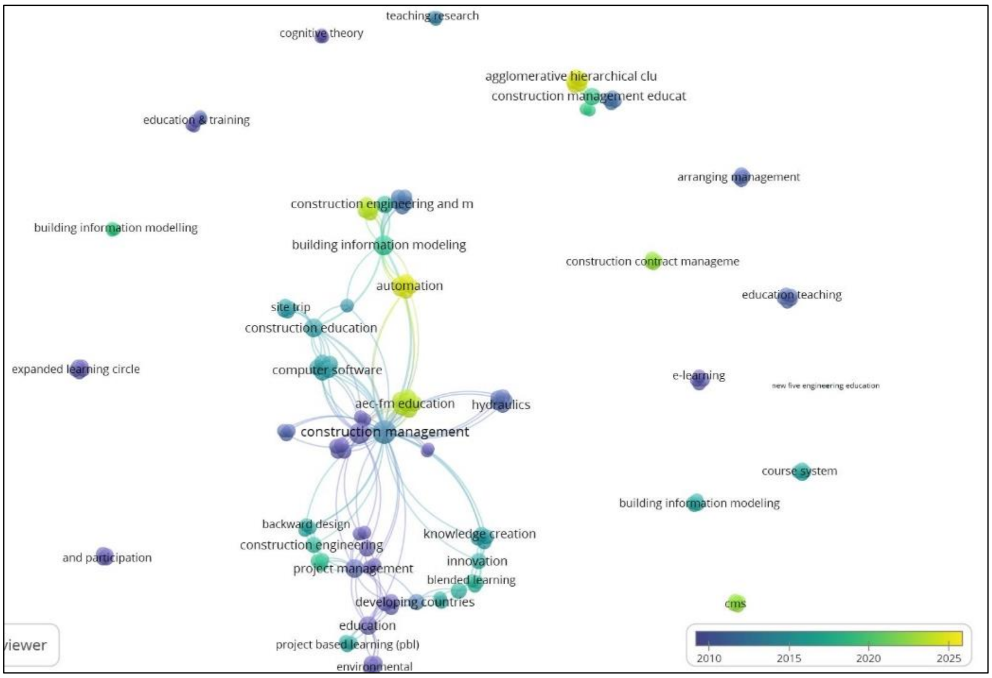

Figure 7: Change in keywords in the analysis over time.

Conclusions

A bibliometric analysis of scientific studies on project and construction management education was conducted. Accordingly, it is seen that there are very limited studies in this field. Most studies have been conducted in the USA, England, China, Scotland, and Australia. Although few studies have been conducted in Turkey, they are included in the mapping due to the high number of citations. This shows that there are few but qualified studies in Turkey. Project and construction management education is important in terms of providing qualified labor force to the construction sector. However, research and studies on this subject are carried out in certain universities in the world. In Turkey, limited studies have been conducted by Istanbul Technical University and Çukurova University. There were no studies in the relevant field until the beginning of the 2000s; it was observed that there was an increasing intensity of studies between 2010 and 2015. After 2015, it was determined that there was a decrease in the number of studies conducted. When the keyword analysis was analyzed, it was observed that studies on the content and quality of education in project and construction management education gained intensity between 2010 and 2015. Since 2015, it has been determined that studies examining the relationship between education and technology have gained weight.

The importance of planning, project management and construction management in the increasingly complex construction sector is increasing day by day. It has become a necessity to provide a qualified workforce to manage, plan and implement the processes in the construction project. In this context, the increase in studies in this field at universities will contribute to the development of the construction sector.

References

Aliu, J., Oke, A. E., Kineber, A. F., Ebekozien, A., Aigbavboa, C. O., Alaboud, N. S., & Daoud, A. O. (2023). Towards a new paradigm of project management: A bibliometric review. *Sustainability*, *15*(13), 9967. https://doi.org/10.3390/su15139967

Birgönül, M. T., Dikmen, İ., Özorhon, B., & Işık, Z. (2007). İnşaat Sektörünün Yapım Yönetimi Eğitiminden Beklentileri. 169-179. https://hdl.handle.net/11511/75689

Higher Education Program Atlas. (2024, April 24). Retrieved from https://yokatlas.yok.gov.tr/

İnce, A., & Topraklı. (2019). Türkiye'de proje ve yapım yönetimi eğitiminin üniversite programlarındaki yeri. *Journal of International Social Research*, *12*(65), 403-410. https://doi.org/10.17719/jisr.2019.3456

Karagöz, B., & Şeref, İ. (2019). Değerler Eğitimi Dergisi'nin bibliyometrik profili (2009-2018). *Değerler Eğitimi Dergisi*, *17*(37), 219-246. https://doi.org/10.34234/ded.507761

Taner, Z. T., & Parlak Biçer, Z. Ö. (2021). Endüstri 4.0'ın proje yönetim etmenlerine etkisi. *Politeknik Dergisi*, *24*(4), 1461-1472. https://doi.org/10.2339/politeknik.741566

Web of Science. (2024). https://www.webofscience.com/wos/woscc/summary/6014331a-263b-4f43-8059-85f08e25b156-e59ff2ab/relevance/1

Zupic, I., & Čater, T. (2015). Bibliometric methods in management and organization. *Organizational Research Methods*, *18*(3), 429-472. https://doi.org/10.1177/1094428114562629

Practical/Experimental Work in Natural Sciences Subjects During Distance Learning

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Abstract

The purpose of this research was to explore how distance learning is organized and implemented in the second year of the pandemic, with a focus on the practical/experimental component, which poses a significant teaching challenge within the education system during this time. This study involved reflections from students at the Faculty of Education during their pedagogical practice in elementary schools. Additionally, seven teachers from a private primary school in Kosovo participated in the study. Semi-structured interviews were employed as the research instrument, adopting a qualitative approach. The results of this research shed light on the experiences of teachers, particularly in the field of natural sciences. It was revealed that teachers implemented the practical/experimental component in two primary ways. In some cases, depending on the nature of the subject, teachers conducted the experiments themselves while students observed from a distance. Subsequently, they instructed the students to replicate the experiment and submit a video. In another approach, teachers instructed students to conduct the experiments themselves and present their findings to their peers. An advantage of this method was the widespread availability of cell phones among parents, enabling them to easily capture videos of their children performing the experiments. Without this technology, assigning such tasks would have been challenging. This approach represents a fusion of digital tools and hands-on experience, allowing students to engage in practical activities while discussing their procedures. The study also highlights the challenges encountered by teachers in providing necessary tools, materials, and digital resources for effective distance learning.

Keywords: *distance learning, practical/experimental work, students, teachers.*

Introduction

In recent years, due to the COVID-19 pandemic, the trend towards more effective integration of distance learning into the education system has been observed in nearly every country worldwide. Many countries and Kosovo asked educational institutions to switch to the distance learning process (UNESCO, 2020). Electronic learning (e-learning) is a new way of learning, enabled by communication technology. It refers to the use of electronic devices and today's technologies in teaching and learning processes (Gjokutaj et al., 2016). This educational approach has been described as the process of creating and providing access to learning when the source of information and learner are separated by time or distance or both, as a result of general or learner-specific reasons (IPSHK, 2020). The use of modern educational technologies, during the teaching and learning process, means the use of different electronic devices, such as laptops, tablets and smartphones, of different types and different software, in a very productive way. The use of the Internet and the use of computer networks for teaching and learning purposes and also the use of various electronic platforms (IPSHK, 2020).

However, this period is a lesson and a good opportunity for all countries and for all of us, what is needed and what steps should be taken for the construction and complete standardization of the distance learning system (Osdautaj, 2020).

Challenges of the Distance Learning Process

The e-learning theory model can help educators understand how cognitive load can be categorized and combined with design principles to make technology-enabled learning effective (He, 2021).

One of the difficulties in Albania has been the lack of online materials for distance learning, such as digital tools and textbooks. In general, according to what it has been seen there, this country has developed and is developing the process through video lectures on Albanian television and through existing phone applications, such as Viber and WhatsApp (IPSHK, 2020). The network of digital education advisors has supported teachers and schools principals, providing them with online training on the availability and use of digital resources for pedagogical practice and promoting teaching practices adapted to educational continuity and the progressive reopening of schools and students, working with local authorities to lend and distribute computers to all students (Vincent-Lancrin, 2020). In addition to technological and pedagogical readiness, teacher well-being and work-related stress are also addressed in the studies of Lepp (2021). The teachers in the study by Kim and Asbury (2020) have described the uncertainty at the beginning of a period in distance learning. In addition to general uncertainty, it shows that for teachers the increase in workload was most difficult during distance learning, cited as a major source of stress (Kim & Asbury, 2020). The ability to adapt materials to meet student needs based on available resources takes time and planning (Pryor et al., 2020). Furthermore, a major hurdle in distance education lies in maintaining student engagement.

A less explored yet equally demanding aspect revolved around remote assessment. The ramifications of this challenge varied significantly, influenced by the unique characteristics of each discipline. It prompted two fundamental inquiries: firstly, how to effectively evaluate students in subjects traditionally reliant on written tests, now in a remote setting, and secondly, how to assess subjects heavily dependent on laboratory practices, where hands-on experience is paramount (Almeida & Monteiro, 2021).

Utilizing a diverse range of learning media, ensuring uninterrupted access to the learning environment, and fostering interactions between students, content, and teachers are among the essential strategies to enhance the effectiveness of such platforms (Hassan, 2021).

Hence, the hurdles encountered in implementing distance learning predominantly encompass pedagogical, technical, and social dimensions. Pedagogically, integrating digital tools into formal education poses a significant challenge. On a technical front, ensuring access to appropriate mobile devices and internet connectivity is paramount. Meanwhile, socially, there exists a notable obstacle stemming from insufficient familiarity and proficiency with digital and mobile technologies (Hansson, 2021).

Faculty members from the Faculty of Education in Kosovo also encountered challenges during the pandemic. Given that the Teacher Education program includes both theoretical subjects and an 8-week student teaching practice, they had to swiftly adapt to complete the semester. The teachers utilized various platforms to stay connected with the student teachers. The Ministry of Education in Kosovo organized teaching activities through online platforms such as Zoom, Google Classroom, and Google Meet. As widely recognized, student teaching practice plays a crucial role in allowing future educators to gain practical experience and prepare adequately for their roles as teachers. Bridging theoretical knowledge acquired in academic subjects with hands-on classroom experience is essential, highlighting the importance of effective mentoring in this process.

To gain a better understanding of how primary education teachers implement distance learning, the research primarily focused on their application of the practical/experimental component in natural science subjects. The main research questions, derived from reflections on teaching students and interviews with teachers, were as follows:

From the perspective of students:

1. How do students perceive distance learning?
2. What are students' reflections on the online lesson content?

Interview questions for teachers:

3. How do you establish objectives for the subjects you teach?
4. How has the practical/experimental component evolved in natural science subjects during distance learning?

Methodology

This study aimed to illustrate the organization and execution of distance learning during the second year of the pandemic, with particular emphasis on the practical or experimental component, which poses significant challenges within the education system during this period. The research method employed is qualitative and is based on reflections from teaching students at the Faculty of Education who engaged in pedagogical practice during distance learning in primary education classes for eight weeks.

The study includes reflections from 25 students. Additionally, semi-structured interviews were conducted with seven elementary school teachers from grades 1-5, representing two private elementary schools in Kosovo. Data collection involved interviews with teachers, while for student teachers, data were collected from their tasks within the framework of pedagogical practice in practical schools.

The teacher interviews encompass demographic questions, gathering personal data about the participants such as gender, age, and work experience, along with other questions formulated for the research purpose. Data from the interviews and reflections of student teachers were collected in the second year of the pandemic at the end of the summer semester. Similarly, interviews with teachers were conducted at the end of the school year. Subsequently, responses to each question were analyzed separately and interpreted, with some interpretations presented in tabular form.

Results and Discussions

Below, we present the results derived from the reflections of high school students and interviews with primary education teachers:

- Students' viewpoints regarding distance learning:

Based on the reflections of student teachers, it was noted as a challenging practice. In classrooms observed, not all students had access to electronic platforms. Although the number of participating students did not exceed 25, the lessons persisted. One student mentioned the brevity of the school hour, with students endeavoring to grasp the fundamental aspects of the teaching profession. Lessons commenced daily at 12:00 p.m., followed by an hour with the teacher, alongside television-based lessons. Students emphasized encountering significant hurdles in adapting to the learning process. Teachers responded promptly by implementing scheduled activities. While students are gradually adjusting to this methodology, educators engage them in brief Q&A sessions at the beginning and end of lessons to encourage discussions. During the core segment, a combination of group instruction and individual tasks is utilized. Although textbooks remain the primary instructional resource, direct interaction with students is not emphasized.

- Student reflections on the part of the lesson during the online lesson

From the reflections of student teachers, it was observed that at the beginning of each lesson, the teacher demonstrated a willingness to engage the students, although at times, a sense of uncertainty arose regarding the technology and teaching methods.

Explanation and Demonstration Phase: The teacher endeavored to keep students engaged by utilizing online presentations to explain key concepts. However, students encountered difficulties in comprehending certain parts of the lesson and expressed the need for more direct and personalized communication. In the third part of the lesson, where the teacher aimed to activate and involve the students actively, a sense of difficulty was observed. Students expressed a need for a more supportive and encouraging approach from the teacher to facilitate sharing thoughts and participating in online discussions.

Another student reflected that the teacher used a video to explain the concept of halves and quarters. Using an orange as an example, the teacher demonstrated how to identify the whole, half, and quarter of an object. Then, using a bread illustration, the teacher further explained the concepts of half and quarter. Pictures were utilized to enhance concentration during the lessons and assist the students. Students were encouraged to document their understanding of the lesson in their notebooks. They were tasked with analyzing and solving problems using the acquired knowledge, with collaboration between teachers and parents. A drawback of this method is the lack of interactivity with the students; everything is conducted solely via television, without direct teacher demonstration. In Kosovo, lessons were organized through various applications (Zoom, Viber, E-mail, Google Classroom, Skype) by teachers of classes. The focus was on tasks from the lessons via public television, along with feedback related to these tasks. Primary school children followed short 20-minute lessons on television, and then connected online with their classes and teachers (KEC, 2021).

- Interview with children about online learning:

Another task assigned to the students was to conduct interviews with friends via phone or other devices to assess how the teaching/learning process was progressing. They were asked about their engagement, the benefits of this method, and to identify any weaknesses in this form of teaching/learning. According to the students' reflections, the interviews were conducted with children from the second and third grades.

Here are some children's responses: "I like homeschooling, but I miss seeing my friends and the teacher in the classroom. Online learning is difficult for me, but my parents help me a lot. I miss playing in the schoolyard, but I hope we can go back soon and see friends; it's not the same as being in school. I understand online learning better when the teacher asks questions and we have discussions. I'm learning to be more focused because my parents help me. But we miss playing with friends and the moments when we have books in hand."

- Is the lesson understandable?

Some children's responses: "The lesson is easier to understand with the teacher because our teacher explains, and we are also asked questions. On TV, we just follow along without interaction."

Another child remarked, "Yes, but it's not as good as being in class. Our teacher is very good and tries her best to make it interesting, but it's not the same without the feelings when we work together with our friends. My parents helped me, but at the same time, I feel like I have more questions. I hope we can go back to school as soon as possible to be with our friends and the teacher."

- Have you developed any activity in any specific subject?

A student responded, "I prepared an activity in the subject 'Man and Nature' when we learned about balance. I did this at home with a sturdy stick and placed books on both sides to balance it." Another child mentioned that they received a recipe on how to prepare plasticine at home and used it to create different shapes, categorizing them into healthy and unhealthy foods. Task clarification occurred via phone communication facilitated by the establishment of Viber and WhatsApp groups for parents.

In this section, we present the perceptions of teachers, focusing on how they conducted the practical/experiential part with the children during online learning.

- How do you set objectives in a subject that you teach?

According to the teachers, since the lessons had to be conducted remotely, they initially outlined the tasks for the children and explained the day's agenda. However, at the beginning of the week, teachers devised a comprehensive plan, and students were required to submit all tasks to the online platform. Teachers found this method advantageous as it allowed students to submit videos, and photos of their homework, and engage in discussions. Teachers could then review and assess all submissions. One teacher mentioned, "I have 25 students in my class, and when I plan something for the experimental part, I ensure that all the children have the necessary tools. If 24 of them have them and 1 doesn't, then I modify the experiment. It's crucial to understand what students can and cannot do."

- How has the practical/experimental part developed in natural science subjects during distance learning?

According to the teachers, they first determine what tasks students can complete from home, or if any materials need to be purchased. Additionally, the teachers mentioned two approaches they use. Firstly, students receive instructions on the task, and each student explains their process with a video. The second approach involves teachers demonstrating the experiment or exercise, and then instructing the students to replicate it and send videos of their own attempts.

For instance, experiments involving eggs, balloons, or creating a volcano using food materials were mentioned. One teacher explained that for experiments requiring other materials, students are required to come to school between 8 and 12 o'clock to collect the necessary items and conduct the experiment at home.

In art subjects, such as studying famous artists like Picasso, students watch videos and examine artworks. Each student is assigned a portion of a picture to complete, and parents are asked to record the process. Students work on tablets, and their progress is visible to other students. Additionally, teachers mentioned organizing online dance sessions, which were enjoyable and engaging for students, providing both physical activity and entertainment.

Conclusions

The main challenges included providing necessary tools and materials, digital resources, limited time, student interactivity, etc. In summary, insights gleaned from both high school students' reflections and primary education teachers' interviews shed light on the challenges and dynamics of distance learning. Despite efforts from teachers to engage students through various methods such as online presentations and interactive tasks, students expressed a desire for more personalized communication and support. Additionally, while teachers made efforts to activate students during lessons, there were instances of difficulty in fostering active participation and emotional connection. Although instructional materials like videos and illustrations were utilized, some students felt a lack of interactivity and dependency on screen-based learning. The need for more varied and interactive teaching approaches emerged as a key takeaway from both student reflections and teacher perspectives. Children expressed a mixture of appreciation for the support received from parents, but also a longing for the social interactions and hands-on experiences of traditional classroom settings. They highlighted the importance of teacher interaction and personalized engagement in understanding lessons effectively. These findings shed light on the complex dynamics of remote education and emphasize the importance of holistic approaches to ensure effective learning experiences for young students. Teachers emphasized the importance of thorough planning at the beginning of the week, ensuring that tasks are tailored to suit the remote learning environment and that all students have access to necessary materials. According to the teachers, video sharing is the best part of it because children see each other's work, so they do their work and see other students' work as well. Practical/experimental activities in natural science subjects were approached with creativity and flexibility. Teachers devised various methods, including instructional videos and student-led demonstrations, to engage students in hands-on learning experiences. Some experiments required students to procure materials from school, while others were designed for home-based execution, fostering a blend of experiential learning and parental involvement. In art subjects, innovative approaches were employed, such as collaborative artwork projects inspired by famous artists, enhancing students' creativity and appreciation for art. Additionally, teachers incorporated physical activities like online dancing sessions to promote holistic development and foster a sense of community among students. Overall, these findings underscore the resilience and adaptability of teachers in navigating the challenges of remote education while also prioritizing student engagement, experiential learning, and holistic development. However, there has been a need for continuous adaptation to improve the quality of learning through technology and the variety of information.

References

Almeida, F., & Monteiro, J. (2021). The challenges of assessing and evaluating the students at distance. *Journal of Online Higher Education,* 3-10.

Gjokutaj, M., Hoti, I., & Kadriu, D. (2016). Fjalor termash ne edukim. *Prishtine: Shtepia Botuese "Dukagjini".*

Hansson, P. (2021). Teaching practice online: Challenges in Japan, India and Kenya under pandemic. *Education Response to a Pandemic*, 77-91.

Haracia, N., & Avdiu, E. (2023). The effect of pandemic period on student teachers' professional growth during their student teaching practice. *Journal of Social Studies Education Research*.

Hassan, M. (2021). Online teaching challenges during COVID-19 pandemic. *International Journal of Information and Education Technology*, 41-46.

He, H. (2021). *E-learning theory*. Press Books, 7-11.

IPSHK. (2020). Mesimi ne distance/e-mesimi ne arsimin parauniversitar ne Kosove, ne rrethanat e krijuara nga pandemia Covid-19. Prishtine: Instituti Pedagogjik i Kosoves.

KEC. (2021). Ndikimi i pandemise COVID-19 ne arsimin parauniversitar ne KOSOVË. EU.from: https://kec-ks.org/wp-content/uploads/2021/10/Ndikimi-i-COVID19-ne-Arsimin-Parauniversitar-SHQIP.pdf

Kim, E. L., & Asbury, K. (2020). Like a rug had been pulled from under you: The impact of COVID-19 on teachers in England during the first six weeks of the UK lockdown. *Br. J. Educ. Psychol.*, 1062–1083.

Lepp, L. K. (2021). Teaching during COVID19: The decisions made in teaching. *Educ. Sci., 47*.

Osdautaj, M. (2020). Ecuria e zhvillimit te mesimit ne distance ne disa vende te BE-se dhe ne vendet e ballkanit. Academia.edu.

Pryor, J., Wilson, R. H., Chapman, M., & Bates, F. (2020). Elementary educators' experiences teaching during COVID-19 school closures: Understanding resources in impromptu distance education. *Online Journal of Distance Learning Administration*, *23*(4).

UNESCO. (2020). COVID-19: 10 recommendations to ensure that learning remains uninterrupted. Learning Solutions.

Vincent-Lancrin, S. (2020). Réseau de délégués académiques numériques (Network of digital education advisers). Paris: OECD Publishing.

Gen Z and the Era of Education 4.0 – Reinterpreting Education

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Abstract

Due to the emphasis on internet necessity, this study tends to focus on Industrial Revolution 4.0 and Education 4.0 and the benefits of SEL. Many issues on human [re]evolution in terms of technology support are fruitfully analyzed and discussed starting with the initial notion: the Silent Generation to Gen Z, or Alpha Generation, and the impact of Education 4.0 on this group of people. The gap between the two can be bridged by focusing on Social and Emotional Learning (SEL) and understanding soft and hard skills development comprehensively. This paper explores various arguments related to conceptualizing the novel relevance of Education 4.0, teachers, learners, technology, and the environment. In addition to students' learning independence, instant connectivity with out-of-class people, and the emergence of Artificial Intelligence are sought to be relevant to Education 4.0.

Keywords: *Alpha generation, Gen Z, education 4.0, industrial revolution 4.0.*

Introduction

Social changes that are considered as social (re)evolution(s) have impacted societal changes in every field, such as education, economy, employment, and entertainment (Schwab, 2016; Hussin, 2018; Himmetoglu et al., 2020; Persada et al., 2020; Miranda et al., 2021; González-Pérez & Ramírez-Montoya, 2022). Humanity has experienced different notions for different generations, each evolving and contributing to the improvement of human life. Let's start for example, the 1928-1945 Silent Generation, the 1946-1964 Boomers (especially in the US and developed nations), followed by Generation X (Gen X) between 1965-1980, then Millennials also known as Generation Y (Gen Y) people born between the early 1980s and the late 1990s, followed by Generation Z (Gen Z), 1990 - 2010, being very familiar with the internet, or, nowadays Gen Alpha (people born from 2010-2024), the successor of Gen Z, Rothman (2016, p. 2) mentions nicknames for Gen Z "the Generation 2020, Internet Generation (IGen), Digital, Natives, Screensters, and Zeds." As the study deals with people and the education of Gen Z and Alpha Gen, the terms Gen Z and Alpha Gen will be used interchangeably.

Literature Review

Generation Z are digital natives i.e., they are influenced by technology, social media, and instant connectivity. Generation Z is eager to adopt and adapt innovative technologies for everyday usage in learning and for entertainment following their own learning pace. To this, this study aims to discuss Gen Z and Education 4.0 by analyzing various researchers' studies.

Regardless of the generational cohort to which humanity belongs (Gen Y, Z, etc.), its trajectory remains closely intertwined with the Industrial Revolution (IR). Concerning people and generation terms, education, and industry " the term Industry 4.0 stands for the fourth industrial revolution" Jeevitha & Ramya (2018, p.2). Moreover, they (Jeevitha & Ramya, 2018) name Industry 4.0: The Industrial Internet, and the people of this generation are Digital 4.0 champions. As such, González-Pérez and Ramírez-Montoya (2022) argue that "It is necessary to analyze the curricula holistically to balance the various objectives of education with the soft and technical competencies required for the 4.0 Industrial Revolution 4.0" (González-Pérez & Ramírez-Montoya, 2022 p.2).

Before discussing IR 4.0, Schwab (2016), Jeevitha & Ramya (2018) explicitly explained the previous stages of IR, i.e., IR 1.0 was based on water and steam power that mechanized production, IR 2.0 was based on electric power to create mass production, assembly line. IR 3.0 was more advanced as it was based on information technology to automate production, electronics, and computers. Whereas the last-nowadays networking system, cyberspace i.e., the internet belongs to Revolution 4.0.

IR 4.0 is based on the digital revolution, i.e., the possibilities of the emerging technology. Hussin (2018) elucidates the relationship between the Industrial Revolution (IR) and Education 4.0. Hussin (2018) and Fisk (2017) argue that Education 4.0 is a response to the needs of Industry 4.0. That is, education 4.0 can be seen as a new model that relates "learning, student, teacher, and school according to needs of Industry 4.0" (Himmetoglu et al.,2020, p.14). This education includes learners of Generation Z, i.e., digital natives who entail collaborative skills, collaborative projects, problem-solving, creative thinking, critical thinking, interactive environments, interactive games, and communication skills that develop autonomous learning (González-Pérez and Ramírez-Montoya, 2022; Rothman, 2016). Gen Z students are so revolutionized by technology (Hussin, 2018) and are very active on the internet (Persada et al., 2020). The necessity of internet usage became even more apparent during the COVID-19 pandemic when all institutions shifted to remote work, a trend that continues today within the Alpha Generation. They are perceived as people being good at multitasking, or called task switching generation (Rothman, 2016). This reliance on the internet has increased significantly for every task, shifting to the term: the Alpha Generation. This generation i.e., nowadays citizens require 21st-century skills, knowledge, and attitudes to navigate the digital, sustainable, and social aspects of the world ethically and humanistically (González-Pérez & Ramírez-Montoya, 2022).

Based on the generation and the Industrial Revolution notions, the study aims to discuss the distinctions between generations and IR, and its principles. Precisely, the impact of educative innovations/modifications of the nowadays generation: the Gen Z/ Alpha Gen.

The study posed the following questions:

- What are the learners' benefits belonging to Gen Z/Alpha Gen?
- How can Social and Emotional Learning (SEL) contribute to the well-being of learners as Gen Z/Alpha Gen?

In this era of education, students easily share their educational content via the internet which enables Learners Generated Content (LGC) (Persada et al., 2020). Education 4.0 alters teachers' responsibilities. i.e., learning is the student's responsibility, whereas the teacher's role is to support this transition (Hussin, 2018). Gen Z learn while being kinesthetic and/or experiential and prefer to learn by being active participants in learning rather than being spectators or readers (Rothman, 2016). When discussing the learners nowadays, the Alpha Generation, these learners have become more autonomous, less teacher-dependent, and less–book-dependent, more flexible in every field, including language learning. This is also supported by González-Pérez and Ramírez-Montoya (2022) who argue that the educational paradigms shaping the 21st century prioritize the development of holistic competencies through the integration of technological tools. Consequently, effective teaching and learning strategies must be implemented to meet these goals (p.6).

In addition, in today's globalized world, where knowledge of various cultures is essential, the demand for English as a second language remains paramount, particularly in the age of the internet. There is a shift from BALL (Book Assisted Language Learning) to CALL (Computer Assisted Language Learning), as all this generation needs are technology, social media, and instant connectivity. Naturally, achieving globalization necessitates the use of an international language.

To this, Jeevitha & Ramya (2018) were farsighted; they predicted that the Fourth Industrial Revolution would soon bring significant changes to every aspect of life. And when discussing education, the learners have become (and are becoming) self-learners. Although self-learners, every generation needs educational innovations. "Educational innovation is an evolution of teaching and learning methods and techniques, which are driven by new social, political, cultural, and technological trends" (González-Pérez and Ramírez-Montoya, 2022 p.7).

González-Pérez and Ramírez-Montoya (2022 p.24) continue arguing that for an institution looking to integrate an Education 4.0 framework, it's crucial to comprehensively address skills development in students, teachers, and administrators, encompassing both soft and hard skills. Naturally, as pointed out by the WEF (World Economic Forum, 2016), Social and Emotional Learning (SEL) is important in modern society. SEL impacts the 21st century's social needs, such as collaboration, communication, and problem-solving. Education 4.0 emphasizes the involvement of global organizations that drive the discourse on learning, national-level entities that promote this discourse, and individual stakeholders who impact it. It also addresses strategies for fostering collaboration among these stakeholders. As pointed out by González-Pérez and Ramírez-Montoya (2022, p. 3), Education 4.0 i.e., education of the 21st century identifies teaching and learning strategies that contain 4.0 components, their learning dimensions; organized into six categories: "(1) technological enablers, (2) organizational enablers, (3) digital competency teaching, (4) soft skills learner, (5) hard skills learner, and (6) pedagogies." These are the main issues that Education 4.0 needs trumpeting (p.3),

WEF (2016) voices understanding of SEL and how to foster it, its linkage to traditional learning, and the long-term positive outcomes. "Teachers of Education 4.0 are defined as everybody, everywhere and seen as innovation-producing sources" (Himmetoglu et al., 2020, p.13). As modern society seeks collaboration, Education 4.0 and SEL are sought to be fundamental connectors.

It is evident that strategies that support Social and Emotional Learning (SEL) presented by the World Economic Forum (2016), such as those that encourage learning, break down learning into smaller coordinated pieces, create a safe learning environment, develop a growth mindset, foster relationship, allow time to focus, foster reflective reasoning and analysis, guide students' interest to discovery, provide appropriate challenges provide clear learning objectives targeting explicit skills and use hand-on approach. This is best achieved by Gen Z as they welcome challenges, as they are fully engaged in their learning process (Hussin, 2018; Rothman, 2016), adding a highly interactive learning environment, active collaboration with other members, and utilizing digital tools and online forums. Miranda et al. (2021) best summarize Education 4.0 presenting the differences i.e., the transition from Education 1.0 to Education 4.0 adding these categories: period, philosophy, educator's role, student's role, approach, learning outcomes, enablers, information sources, facilities, and industrial technology.

> "Education 4.0 is the current period in which Higher Education institutions apply new learning methods, innovative didactic and management tools, and smart and sustainable infrastructure mainly complemented by new and emerging ICTs to improve knowledge generation and information transfer processes. Combining these resources during teaching-learning processes will support the training and development of desirable critical competencies in today's students". (Miranda et al.2021, p.4)

Hussin (2018) mentions the acronym BYOD (Bring Your Own Device) approach, which enables students to freely choose learning tools and become creative in their learning. The attainment of these objectives is facilitated through the incorporation of pedagogical methodologies and the integration of nowadays supportive learning technologies. On the other hand, WEC (2016) adds that Ed-tech adoption is still hampered.

Even Dunwill (2016) predicted the future appearance of the average classroom, and his forecasts have proven accurate.

a) A huge change in the layout of the classroom
b) Virtual and augmented reality will change the educational landscape
c) Flexible assignments will accommodate multiple learning styles
d) MOOC and other online learning options will impact secondary education

Dunwill (2016) in his study focused on the changes that would take place in the teaching method and the setting of the learning process. The layout of the classroom has gradually changed from neat rows and chairs to flexible seating arrangements enabling both individual and collaborative workspaces. Student assignments are no longer in the form of constructed or selected responses only. Alternative assessments have been introduced to accommodate multiple learning styles. Portfolios, project papers, demonstration of skills, and rating scales are among the alternative assessments beingpracticed nowadays. A comparable transformation has occurred even in tertiary education settings across most countries due to the Covid-19 pandemic. i.e., apart from changes in the classroom layout and the types of assessment, all educative levels, including tertiary education institutions have begun integrating Massive Open Online Courses (MOOCs) and other online learning platforms into their teaching and learning methodologies, also mentioned by Hussin (2018). Important to mention in this era of Education is the application of Artificial Intelligence (AI), a discipline within computer science, that concentrates on creating systems and machines capable of executing tasks that traditionally demand human intelligence (Lima, et al., 2024).

Miranda et al (2021) propose and succinctly explain the four core components of Education 4.0: Based on them (Miranda et al, 2021), the first component is students' competence i.e. student's training and development for critical competence, the second component proposed is Learning Method(s), i.e. enhancing innovative teaching and learning methods suitable for student's needs and wishes, the third component deals with the application of Information and Communication Technologies (ICTs) in teaching and learning, and the fourth component includes Infrastructure, i.e., modern learning facilities, and services and systems that enhance the learning process. Moreover, educators in various countries have shown awareness of the use of educative technologies that encourage learning, including SEL (World Economic Forum, 2016).

WEF (2016) succinctly describes the students' 16 skills needed for the 21st century. That is, the 21st-Century Skills that include lifelong learning (WEF, 2016, p.4) are described below:

- "Foundational Literacies

How students apply core skills to everyday tasks

1. Literacy
2. Numeracy
3. Scientific literacy
4. ICT literacy
5. Financial literacy
6. Cultural and civic literacy

- Competencies

How students approach complex challenges

7. Critical thinking/ problem-solving
8. Creativity
9. Communication
10. Collaboration

- Character Qualities

How students approach their changing environment

11. Curiosity
12. Initiative
13. Persistence/ grit
14. Adaptability
15. Leadership
16. Social and cultural awareness" (WEF, 2016, p.4)

Indeed, while there is significant potential in leveraging AI to revolutionize education and better equip students for the complexities of the 21st century exploring how AI can be effectively integrated into educational systems while considering its benefits and potential drawbacks is essential to ensure that it truly enhances learning outcomes and prepares students for future challenges (Lima et al., 2024), there are still uncertainties regarding its full impact and efficacy, especially when discussing SEL. SEL offers lots of benefits in lifelong learning. It focuses on academic achievements, via students' collaboration and communication with one another (WEF, 2016). This is best achieved via a flipped classroom. Based on Himmetoglu et al. (2020), a flipped classroom is a teaching-learning approach where students are responsible for their learning. Practice-based learning is emphasized and it provides students with individualized educational opportunities and enables learning to occur anywhere and anytime, their learning is focused on technology, i.e., the Internet. The relationship between Education 4.0 and the flipped classroom is also mentioned by Hussin (2018) adding interactive learning in class and out of class.

Methodology

The methodology of this study discusses other researchers' attitudes towards the above-mentioned issues. They are analyzed and synthesized in the literature review then interpreted based on our point of view.

Discussion

As mentioned by Jeevitha & Ramya (2018), digitization will permanently impact our living and working environments. Nowadays teachers need tech training and tech methodology, as well as tech equipment to meet the Gen Z/Alpha Gen students' learning preference(s). Schwab (2016), Lima et al., (2024) mention the mandatory development of a comprehensive view of how technology is affecting people's lives and how it reshapes economic, social, cultural, and human environments in a global aspect, which all embrace factors of SEL. When discussing learners' benefits belonging to Gen Z/Alpha Gen, both IR 4.0 and Education 4.0 embrace 4cs-collaboration, communication, critical thinking, and creativity (Bekteshi, 2017). To become more globalized, the stakeholders must adapt and collaborate with other institutions and foster appropriate applicable approaches that promote education for the specific generation and its SEL. This also corresponds with the second study question regarding SEL's contribution to the well-being of learners as Gen Z/Alpha Gen.

In the contemporary educational landscape, learning occurs via the Internet, both at home and within traditional school settings. These prove the necessity of the application of novel, diverse, and often complex learning strategies and methodologies, always bearing in mind technology and internet usage. Or, as mentioned by González-Pérez and Ramírez-Montoya (2022), and Lima et al., (2024) educational innovative initiatives need to correspond with the current social contexts, adding strategic planning essential to furnish classrooms with the necessary technological infrastructure and digital resources, ensuring readiness for the evolving educational landscape.

The study discusses that nowadays' Gen Z/Alpha Gen and Education 4.0 are well-tuned. They are best described by the principles of teaching and learning in the era of Education 4.0, as listed below:

- Learners of the Gen Z/Alpha Gen self-learn and apply the 4Cs autonomously by embracing technology
- Learners of the Gen Z/Alpha Gen actively contribute to the self-paced learning process. i.e., the teaching is conducted based on the learners' needs and wants.
- Learners of the Gen Z/Alpha Gen are becoming more actively engaged in Artificial Intelligence applications.
- Learners of the Gen Z/Alpha Gen learn SEL skills, and life skills alongside factual knowledge.
- Learners of the Gen Z/Alpha Gen take an active role in shaping the learning process and making meaningful contributions.
- The Gen Z/Alpha Gen can find opportunities to utilize their skills in practical, real-world situations outside of the classroom environment, promoting lifelong learning.
- Promote active communication among learners through structured and achievable tasks, primarily conducted online.
- The Gen Z/Alpha Gen and Education 4.0 aim to encourage innovative teaching approaches and methodologies, and introduce appropriate pedagogical practices by challenging learners for more learning.
- The Gen Z/Alpha Gen are emotionally related to technology, social media, and

instant connectivity.

An evaluation of sustainable learning in Education 4.0 is currently being conducted through Artificial Intelligence, modeling knowledge management scenarios, and participatory international collaboration. The motivation behind this application is simple which needs more trumpeting: Alpha Gen excels in professional interaction and information extraction**.**

Conclusion

Students' learning preferences have changed. This study raises issues related to the 21st-century needs teaching tendencies. Taking on the teaching perspective, it triggers Gen Z's/Alpha Gen needs and wishes. In line with Miranda et al.'s (2021) core components of Education 4.0, to follow the 21st century's trends, modern teachers should apply and design new educational models, appropriate and applicable modern technology teaching tools, and innovative teaching and learning methodologies, utilized in modern infrastructure. It is the teachers' job to adopt their teaching based on student's needs to enable Gen Z/Alpha Gen students to learn and be more creative in their learning (Hussin, 2018; Persada et al., 2020; Lima et al., 2024). Also supported by Schwab (2016), to think strategically about the innovation that is shaping our future.

To conclude, Gen Z/Alpha Gen learning dimensions are exclusive to Education 4.0. When tailoring SEL factors for Education 4.0, AI issues should also be tackled. The specific features and implications promote IR 4.0 and develop intellectual abilities in the field of computing and networking necessary for sustainable development in the field of social, economic, and even environmental issues. This new version of teaching and learning leads to more advanced education: Education 5.0 which focuses on students' learning, communication, collaboration, and emotions, not on technology. Therefore, the Alpha Gen is steadily advancing towards a paradigm of social development, prioritizing considerations such as emotions, abilities, societal impacts, and accessibility in the acquisition of 21st-century information.

References

Bekteshi, E. (2017). The 'Fours Cs - Collaboration, Communication, Critical Thinking and Creativity at The Faculty of Arts (Flup), University of Porto, Porto, Portugal. *Journal of International Social Research*. 10(50), 56-62. DOI: 10.17719/jisr.2017.1638

Dunwill, E. (2016). *4 changes that will shape the classroom of the future: Making education fully technological*. Accessed from https://elearningindustry.com/4-changes-will-shape-classroom-of-the-future-making-education-fully-technological

Fisk, P. (2017). *Education 4.0 ... the future of learning will be dramatically different, in school and throughout life*. Retrieved from: https://www.peterfisk.com/2017/01/future-education-young-everyone-taught-together/

González-Pérez, L. I., & Ramírez-Montoya, M. S. (2022). Components of Education 4.0 in 21st Century Skills Frameworks*: Systematic Review*. *Sustainability*, 14, 1493. Retrieved from: https://www.mdpi.com/2071-1050/14/3/1493

Himmetoglu, B., Aydug, D., & Bayrak, C. (2020). Education 4.0: Defining the Teacher, the Student, and the School Manager Aspects of the Revolution. *Turkish Online Journal of Distance Education-TOJDE* July 2020 ISSN 1302-6488 IODL-Special Issue Article 2. pp.12-28 DOI: 10.17718/tojde.770896

Hussin, A.A. (2018). Education 4.0 Made Simple: Ideas for Teaching. *International Journal of Education & Literacy Studies. IJELS* 6(3): 92-98 ISSN: 2202-9478 Retrieved from: http://www.journals.aiac.org.au/index.php/IJELS/article/view/4616/3541

Jeevitha, T., & Ramya, L. (2018). *Industry 1.0 to 4.0: the evolution of smart factories*. Retrieved from: https://www.researchgate.net/publication/330336790_INDUSTRY_10_TO_40_THE_EVOLUTION_OF_SMART_FACTORIES#fullTextFileContent

Karlos de Sousa Oliveira, K., & André Cavalcante de Souza, R. (2020). Habilitadores Da Transformação Digital Em Direção à Educação 4.0. *Revista Novas Tecnologias na Educação (Renote)*.**2020**, *18*, 1

Lima, L., Lima, R., Matos, J., Leite, F., Júnior, D., Saraiva, A., Carballo, F., Silva, D., Júnior,. L., & Silva, L. (2024). Education 4.0 and the application of AI in teaching. *Navigating through the knowledge of education.* Retrieved from: https://www.researchgate.net/publication/379211618_Education_40_and_the_application_of_Artificial_Intelligence_AI_in_teaching

Miranda, J., Navarrete, C., Noguez, J., Molina-Espinosa, J. M., Ramírez-Montoya, M. S., Navarro-Tuch, S. A., Bustamante-Bello, M. R., Rosas-Fernández, J. B., & Molina, A. (2021). The Core Components of Education 4.0 in Higher Education: Three Case Studies in Engineering Education. *Computer and Electrical Engineering*. 93, 107278. Retrieved from https://www.sciencedirect.com/science/article/pii/S0045790621002603

Persada, S. F., Ivanovski, J., Miraja, B. A., Nadlifatin, R., Mufidah, I., Chin, J., & Redi, A. A. N. P. (2020). Investigating Generation Z' Intention to Use Learners' Generated Content for Learning Activity: A Theory of Planned Behavior Approach. *International Journal of Emerging Technologies in Learning (iJET)*, *15*(04), pp. 179–194. https://doi.org/10.3991/ijet.v15i04.11665

Perić, N., Mamula Nikolić, T., & Delić, T. (2020*)*. Analysis of Attitudes of GenZ Toward Media and Consumption: The Region of Balkans. *QMJ – Quarterly Marketing Journal.* Volume 51; Issue 3; Year 2020 QMJED 51 (3) pp.210-216

Rothman, D. (2016) *A Tsunami of Learners Called Gen Z.* http://www.mdle.net/Journal/A_Tsunami_of_Learners_Called_Generation_Z.pdf

Shwab, K. (2016). *The Fourth Industrial Revolution: What it means, how to respond*. Accessed from https://www. weforum.org/agenda/2016/01/the-fourth-industrial-revolution-what-it-means-and-how-to-respond\

World Economic Forum (2016). *New Vision for Education: Fostering Social and Emotional Learning through Technology*. Retrieved from: https://www3.weforum.org/docs/WEF_New_Vision_for_Education.pdf

Challenges in Developing Virtual Reality Education for Addressing Climate Change

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Abstract

Virtual reality technology will change many of our habits by increasing its user base in the near future. Among these habits, the most significant change will be in people's learning habits. In traditional educational methods, people used to learn through verbal communication, but now they require more visual cues to learn. Television and phone screens have not fully met people's need for visual-based learning. Examples reflected on a two-dimensional plane are not sufficient for learning. Virtual reality technology, the favorite technology of recent times, offers extraordinary opportunities for visual tools to educators. Recognizing the opportunities offered by this technology to educators, scientists have conducted various researches using virtual reality technology as an educational tool. To enable researchers to conduct more studies in this field, there is a need for a guide on developing virtual reality education. Because there are many different software alternatives and visualization tools for educational development. And all alternatives bring different challenges to developers. This study identifies the difficulties encountered in an education prepared with virtual reality technology and offers recommendations to readers. All these challenges and recommendations are exemplified through the climate change awareness education we have developed.

Keywords: *climate change, education, virtual reality*.

Introduction

The widespread use of mobile devices has not only changed the lives of a segment of society but also impacted everyone's lives. When the internet first began to be used, only those with computers could access it, and very few people had computers. However, today, almost everyone has a mobile phone, and everyone can access the internet through these mobile devices. Thus, mobile devices have changed the lives of every segment of society.

Technological advancements continue to progress with each passing day. The inclusion of artificial intelligence among evolving technologies signals that technology will bring many more innovations to human life. Among all these emerging technologies, one of the most prominent is virtual reality technology. In virtual reality technology, a person typically navigates through a virtual environment using a headset. They interact with virtual objects in a simulated environment and completely disconnect from the real environment (Rismayani et al., 2022). Virtual reality technology is seen by technology companies as the next major technology of the future, and these companies are making astronomical investments in virtual reality technology (Naz, 2023).

Numerous studies have investigated the efficacy of virtual reality (VR) training for addressing climate change. Rismayani et al. (2022) conducted research in the Makassar region, which faces a high risk of flooding due to climate change but lacks public awareness about floods. They presented a VR simulation they developed depicting flood disasters and the necessary precautions to local residents, with 91.3% of participants finding the simulation useful. Meijers et al. (2023) used VR technology and video to simulate a forest fire. Participants were divided into groups, with one watching the fire via video and the other using VR technology. The group using VR technology reported more intense physical reactions and found the fire to be more realistic. Aksel Stenberdt and Makransky (2023) provided waste management education to students using VR technology, noting its effectiveness as an educational tool but emphasizing the need for further research on its optimal use. Markowitz et al. (2018) developed a VR education program on ocean acidification and assessed its effectiveness through open-ended questions, concluding that it was a valuable educational tool based on the analysis of responses. Barnidge et al. (2022) created climate change news using VR technology and assessed its impact on learning. They found that while their VR news increased the sense of presence, it did not significantly contribute to learning.

It has been decided to conduct a study to help researchers who intend to use virtual reality technology in the field of education understand the challenges they may encounter when developing educational content. The aim of the study is to propose an ideal roadmap for researchers who will work in this field and develop educational content.

Research Question: What are the challenges faced in developing education using Virtual Reality Technology, and what are the ideal methods to overcome these challenges?

Method

In our study, which focuses on the challenges encountered in the preparation of virtual reality education, a virtual reality education related to climate change has been developed to better understand the challenges faced by education developers and to address those challenges.

The development process started with research on which visualization tool to select. It was found that there are two main devices commonly preferred by developers for visualization technologies. One of these devices is the HoloLens 2 augmented reality goggles developed by Microsoft. At the beginning of the study, software was developed and experienced with the HoloLens 2 augmented reality goggles. However, due to some problems encountered during these experiences, a change was made in the visualization tool. The main reason for choosing the HoloLens 2 as the visualization tool at the beginning of our study was that it was the most popular goggles in the majority of studies in the literature (Kolaei et al., 2022). However, as we will explain in more detail in the later parts of our paper, some problems were encountered with the visualization performed with the HoloLens 2 augmented reality goggles. Therefore, the Oculus Quest 2 virtual reality goggles, another commonly preferred visualization tool in the literature, was chosen as the visualization tool in our study.

Du et al. (2017) used the Oculus Quest goggles to navigate participants through a three-dimensional building model to gather their opinions on the design. Oculus Quest goggles can successfully display simulations and integrate with game engines. With a battery life of 2 hours, it is sufficient for the scope of our study. Due to all these advantages, the Oculus Quest 2 virtual reality goggles were chosen as the visualization tool in our study.

When it comes to content creation in visualization technologies, it is observed that scientists predominantly prefer the Unity game engine. Providing a few quotes from similar studies in the literature would be beneficial for accessibility. Wolf et al. (2022) preferred the Unity game engine when designing virtual reality training for occupational safety. Participants were shown hazards in the workplace through simulations in virtual reality training. Urban et al. (2022) used the Unity game engine to create an online accessible virtual visualization training platform. Unreal Engine is another software that has been preferred in the literature apart from Unity. However, this game engine has not been as widely chosen as Unity. Additionally, there are many valid reasons for choosing Unity, which will be discussed in the later parts of our paper.

The education we have developed focuses on the effects of climate change on the Earth. When developing the education, we aimed to keep the target audience as broad as possible. Care was taken to use language that participants from all age groups and educational levels could easily understand when watching the education. The education was designed to be visually rich because virtual reality technology is still an unfamiliar technology for many people in today's world. Therefore, we aimed to engage participants by providing visual richness when completing the education, as we aimed to provide participants with an experience. In the education, our goal was not only to provide information to people but also to keep participants' attention at the highest level by taking them to various virtual environments continuously.

The education has been developed as a 5-minute training. Since most participants may not have previously used virtual reality devices, we designed an education where the participant would only be in the role of observer and listener. From the beginning of the education, the participant experienced virtual reality in different environments as if watching a short film. To achieve this, the Timeline editor of the Unity game engine was used.

To develop the game, there was a need for various 3D environments and objects. While it was possible to model and transfer all of these environments and objects to the Unity game engine, designing them required a much longer workload than developing the education itself. Fortunately, the Unity game engine's Asset Store provides users with free virtual environments and objects. The virtual objects required for the education were obtained from free assets available in the Unity game engine's Asset Store.

For the first scenes of the education, a space environment and a rotating Earth were used. This was because the impressive visuals of space and the rotating Earth would be a great introduction for participants. In this environment, participants were informed about the risks of climate change to Earth, the fact that there is no other known Earth to escape to in space, and the need to do something for our planet.

In the other scenes of the education, participants were taken to a forest environment to discuss the importance of forests for us and the decreasing number of forests and animal species. They were then taken to a dried-up lake environment to discuss the decreasing clean water reserves on Earth. In this scene, participants were shown the lake drying up rapidly. In another scene, participants were taken to a desert environment, which was introduced as the future awaiting Earth if necessary, measures regarding climate change are not taken. In another scene, participants were taken to a kitchen scene to provide information about daily tasks for individuals, with a focus on water conservation.

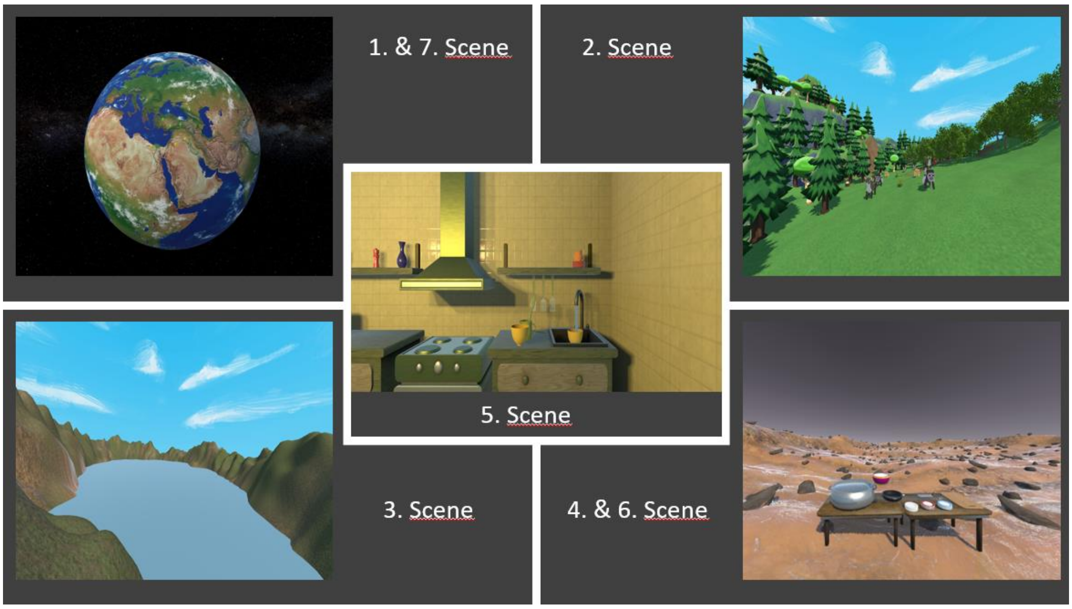

Figure 1: Education scenes.

The entirety of the trainings was experienced by numerous participants from different educational backgrounds. After the viewings, feedback was obtained from each participant regarding the education. The comments of the participants will be reported in the later sections of our paper.

Results & Discussion

During the education development process, it is necessary to determine which visualization tool will be used, even in the early stages of program development. This is because each headset has a different program development method. Even if the same software development tools are used, the plugins that need to be installed on the device vary at the beginning of the software development process. These plugins are not capable of running the education on each visualization headset. The necessity of pre-selecting the headset to be used in the education is one of the most prominent challenges in the education development process.

In this study, a choice had to be made between the most commonly used Hololens 2 and Oculus headsets for education development. Both headsets were liked and recommended by users. Consideration was given to the Hololens 2 augmented reality headset's ability to perceive the environment, better detect hand movements, and interact with real objects and virtual objects. Due to these superior features, the education was developed based on the Hololens 2 augmented reality headset. All plugins were installed through the Hololens 2 augmented reality headset in the Unity game engine.

It was observed that the tested Hololens headsets did not provide the desired efficiency for virtual reality education. Hololens headsets are advanced augmented reality headsets developed with superior technology. They have superior features that will provide users with unique experiences such as positioning capabilities and hand movement detection. However, in virtual reality educations, users expect to enter a virtual environment and experience a visual spectacle. In the climate change education conducted by fully integrating users into the virtual environment, it was observed that all graphics and images could not be displayed flawlessly with the Hololens 2 device. As real-world objects are also visible in the virtual environment, users cannot focus on virtual environments. Additionally, in a lit environment, the disadvantages of the Hololens 2 augmented reality headset are exacerbated. This is because the image is reflected onto a transparent glass in Hololens 2, and when sunlight reflects onto this glass, virtual objects cannot be displayed clearly.

Considering all these disadvantages, we recommend researchers developing education on visualization technologies to choose headsets with superior features in virtual reality rather than augmented reality headsets if they have expectations of roaming in virtual environments.

In this study, Unity game engine was preferred as the program development software. It was observed that Unity, along with offering plugins that would be useful for developers, also provided developers with useful plugins. However, to develop high-quality educations in this field, it is mandatory for users and researchers to receive basic training in Unity. Researchers who want to reflect all the graphics they imagine in the education should also receive advanced Unity training and C# programming language training. The requirement of programming and software knowledge is one of the main challenges encountered in developing virtual reality education. However, in the educations developed, high satisfaction was obtained from the qualifications of the Unity game engine. It is not appropriate to express an opinion on the qualifications of other game engines, and this comment should not be perceived as a comparison. However, the competence and adequacy of the Unity game engine were determined in this research.

The education was shown to participants, and feedback was obtained on the success of the education. Participants were selected from individuals who had never experienced virtual reality education before. All participants reported that virtual reality education was more effective and engaging than traditional education methods. The main challenge in using virtual reality education compared to traditional education methods is the personalization of visualization tools. It is not suitable for group classes. A separate personal headset is required for each participant. With the development of virtual reality technology, it is thought that personal headsets will become widespread, like mobile phones. This challenge will be overcome with the development of technology.

Another challenge is the limited battery life of visualization headsets, which is typically around 2 hours. Considering that the average daily education duration in Turkey is around 6 hours, a 2-hour usage time is quite short. Overcoming this challenge would only be possible with the advancement of headset technology and extending the battery life to at least 12 hours.

The fact that users had never used virtual reality technology before was not seen as a challenge. This is because, during the education development, the videos were prepared considering this inadequacy of users. There was no need for users to control anything during the education. Only the process of opening and closing the education required controlling the headset. This need was easily met by the researcher supervising the education. Additionally, the Unity game engine has the capability to assign desired commands to the controller, which is part of the Oculus Quest headsets. Ensuring that users can easily control the education is within the capabilities of the developer.

Developing three-dimensional models for virtual reality technology is one of the main challenges in education development. This is because developing three-dimensional models requires both expertise and intensive effort. The Unity game engine does not have sufficient features for developing three-dimensional models. Although some models can be developed with simple geometric shapes, the capabilities of these models are quite limited. Users need to resort to other programs to develop three-dimensional models. Models developed in programs such as 3Ds Max, Revit, Sketchup, and many other three-dimensional model development programs can be transferred to Unity. After designing the desired model, users need to transfer this model to Unity and then develop the game. Transferring dozens of models required for an education one by one from these programs to Unity is a quite laborious and time-consuming process. To overcome this challenge, the Unity game engine's Asset Store was utilized. Many users share the three-dimensional models they develop on the Unity Asset Store. Users can share their models for free or for a fee. Developers, if they find models shared on the asset store suitable for their own educations, can develop education by purchasing them. In the education developed in this study, models from the free shared models on the Asset Store were preferred. We recommend researchers who will develop education using virtual reality technology to design their education based on the models available in the Unity Asset Store after reviewing them.

Conclusion

Virtual reality technology is one of the immersive and evolving technologies of our time. In the education sector, virtual reality technology should become dominant and replace traditional educational methods. Researchers need to conduct more research on education prepared with virtual reality technology. When the research conducted in this field is examined, it is observed that the difficulties of education prepared with virtual reality technology are identified, and there are no studies to guide developers. Research mostly focuses on the effects of education on individuals.

In this study, a virtual reality education on climate change was designed. The challenges encountered in the developed education were identified, and recommendations were reported.

In virtual reality education, the same education was developed on both Hololens 2 and Oculus Quest 2 glasses. However, it was found that virtual reality glasses yielded more successful results in education designed for navigation within the virtual environment. Unity game engine was used in game development, and its adequacy and competence were determined. However, it was emphasized that education developers need to have at least basic programming knowledge. It was stated that the three-dimensional virtual models needed during game development were obtained from the Unity Asset Store.

The challenges in virtual reality technology will be overcome with an increase in research and the advancement of technology. It is believed that technology will soon replace traditional educational tools.

In future research on the use of virtual reality technology in climate change education, we recommend including different learning strategies and testing the effectiveness of education in comparison to other teaching methods. Furthermore, we suggest enhancing collaboration between researchers developing education on climate change using virtual reality technology.

References

Aksel Stenberdt, V., & Makransky, G. (2023). Mastery experiences in immersive virtual reality promote pro-environmental waste-sorting behavior. *Computers & Education*, *198*, 104760. https://doi.org/10.1016/J.COMPEDU.2023.104760

Barnidge, M., Sherrill, L. A., Kim, B., Cooks, E., Deavours, D., Viehouser, M., Broussard, R., & Zhang, J. (2022). The effects of virtual reality news on learning about climate change. *Mass Communication and Society*, *25*(1), 1–24. https://doi.org/10.1080/15205436.2021.1925300

Clegg, N., & Olivan, J. (2021). *Investing in European talent to help build the Metaverse | Meta*. https://about.fb.com/news/2021/10/creating-jobs-europe-metaverse/

Du, J., Shi, Y., Zou, Z., & Zhao, D. (2017). CoVR: Cloud-based multiuser virtual reality headset system for project communication of remote users. *Journal of Construction Engineering and Management*, *144*(2), 04017109. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001426

Kolaei, A. Z., Hedayati, E., Khanzadi, M., & Amiri, G. G. (2022). Challenges and opportunities of augmented reality during the construction phase. *Automation in Construction*, *143*. https://doi.org/10.1016/j.autcon.2022.104586

Markowitz, D. M., Laha, R., Perone, B. P., Pea, R. D., & Bailenson, J. N. (2018). Immersive virtual reality field trips facilitate learning about climate change. *Frontiers in Psychology*, *9*(Nov), 421569. https://doi.org/10.3389/FPSYG.2018.02364/BIBTEX

Meijers, M. H. C., Torfadóttir, R. "Heather," Wonneberger, A., & Maslowska, E. (2023). Experiencing climate change virtually: The effects of virtual reality on climate change related cognitions, emotions, and behavior. *Environmental Communication*, *17*(6), 581–601. https://doi.org/10.1080/17524032.2023.2229043

Naz, S. (2023). *7 Ways virtual reality will change our lives*. https://www.arpatech.com/blog/7-ways-virtual-reality-will-change-lives/

Rismayani, Paliling, A., Nurhidayani, A., & Pineng, M. (2022). Fundamental design of flood management educational games using virtual reality technology. *International Journal of Online and Biomedical Engineering (IJOE)*, *18*(03), 19–32. https://doi.org/10.3991/IJOE.V18I03.27787

Urban, H., Pelikan, G., & Schranz, C. (2022). Augmented reality in AEC education: A case study. *Buildings*, *12*(4), 391. https://doi.org/10.3390/BUILDINGS12040391

Wolf, M., Teizer, J., Wolf, B., Bükrü, S., & Solberg, A. (2022). Investigating hazard recognition in augmented virtuality for personalized feedback in construction safety education and training. *Advanced Engineering Informatics*, *51*, 101469. https://doi.org/10.1016/J.AEI.2021.101469

Determining Critical Barriers to Waste Management in Turkey

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Abstract

Over the past few decades, there has been a notable surge in the generation of construction and waste, presenting formidable challenges to the construction industry and imperiling environmental sustainability. The construction industry encounters various barriers that impede the implementation of construction waste management (CWM) strategies. Identifying the main barriers of CWM should be the first step towards solving this problem. Therefore, this study aims to identify the critical barriers to CWM in the Turkish construction industry. First, a systematic literature review was conducted within the framework, and 54 barriers were identified. The barriers were evaluated through a questionnaire with a 5-point Likert scale of project architects, project engineers, site supervisors, and contractors in the Turkish construction industry (162 respondents in total). Reliability analyses of the questionnaires are performed using SPSS 22 software. Then, normalized mean value (NMV) analyses were conducted on the obtained data to determine the critical barriers (CBs) to CWM. Consequently, among 54 barriers, this study highlighted 36 CBs to CWM in the Turkish construction industry that lack of education of workers, inadequate protection during material unloading, equipment failure, time pressure, and lack of information about material dimensions were the top five significant barriers.

Keywords: *construction waste, demolition waste, Turkish construction industry, waste management.*

Introduction

The surge in population, along with the expansion of infrastructure and superstructure projects, has led to heightened construction activities, resulting in increased construction waste (Reid et al., 2016). This surge has caused various adverse impacts, particularly on the environment. Consequently, there is a pressing need to develop effective construction waste management to address these issues and proactively prevent waste, enhancing positive added value and contributing to environmental sustainability.

Reducing construction waste not only benefits the environment by minimizing pollution, reducing landfill use, and decreasing the consumption of non-renewable raw materials but also contributes to the well-being of future generations (Doust et al., 2020). Additionally, stakeholders such as contractors and clients stand to achieve financial efficiencies through improved waste minimization practices. Therefore, implementing effective construction waste management practices becomes crucial to mitigate environmental damage (Yang et al., 2020).

Construction waste management (CWM) is a potential solution, but it is a global concern affecting developed and developing nations. Scholars from developed countries such as the USA and China (Aslam et al., 2020) and the United Kingdom (Ajayi et al., 2015) have made noteworthy strides in advancing CWM practices. Meanwhile, researchers from developing countries like Costa Rica (Abarca-Guerrero et al., 2017), Bangladesh (Hasan et al., 2022), Pakistan (Nawaz et al., 2023), United Arab Emirates (Al-Hajj & Hamani, 2011), and Egypt (Daoud et al., 2023) - where construction stands as a critical economic activity - have increasingly demonstrated keen interest in promoting CWM-related research. Notably, there is a great interest in Turkey also. Polat et al. (2017) reported a significant level of the cause of material waste. Ulubeyli et al. (2018) identified the technical features and operational capabilities of Turkey's existing construction and demolition waste recycling plants. Tas and Can (2023) compared one modular and one prefabricated building regarding material waste during construction. All previous studies significantly contributed to the literature conceptually and practically. However, determining the critical barriers to CWM is still lagging. Although there are several obstacles to effective CWM, it is important to know which of these criteria are critical and their order of importance to prioritize the measures to be taken. Therefore, this study aims to comprehensively and realistically identify the critical barriers to CWM. To achieve this objective, the study examines the critical barriers to effective CWM across all building construction phases, from design to demolition. The obstacles to CWM at each building construction stage are identified, and critical ones are highlighted and ranked. Finally, corresponding recommendations are provided.

Methodology

This study is specifically focused on the scale of the Turkish construction industry, with its target population being professionals such as architects, civil engineers, construction site chiefs, and contractors actively involved in Turkey's construction sector. The research framework is structured into three consecutive phases: firstly, a systematic literature review is conducted to identify potential barriers that will be the basis for the questions in the questionnaire form. The second phase includes the administration of a 5-point Likert scale questionnaire derived from a systematic literature review and, subsequently, the determination of the critical barriers to CWM based on participants' responses.

Systematic Literature Review

The research employed a Systematic Literature Review (SLR) as the first phase of the methodology, aiming to identify and critically assess relevant studies while collecting and analyzing data derived from these studies (Liberati et al., 2009). In line with this approach, an SLR was adopted in this study to systematically gather data from a transparent and critical perspective (Macpherson & Jones, 2010) on potential barriers to CWM in the Turkish construction industry.

The protocol used for screening the Web of Science (WoS) database, which encompasses a comprehensive collection of nearly all significant research (Yu et al., 2022), is outlined as follows: (ALL FIELDS) “construction waste” OR “waste management” AND “construction” AND “barriers” OR “challenges” OR “obstacles.” The specified timeframe for the search ranged from 2000 to 2022.

The search initially resulted in 1599 publications. Subsequently, well-defined inclusion and exclusion criteria were applied during the elimination stage. Within this scope, all acquired documents underwent review, leading to the exclusion of 1513 records. Ultimately, 86 articles were selected to form the basis for the survey questionnaire.

Structuring Questionnaire and Data Collection

Conducting an SLR, the 86 chosen studies for constructing questionnaire items underwent detailed examination across eight primary categories (design, supply chain, transportation of material, planning and management, material storage, construction stage, human resources, and external factors), leading to the identification of a comprehensive set of 54 barriers to CWM. Following this, a questionnaire structured based on these barriers on a 5-point Likert scale was distributed to architects, civil engineers, construction site chiefs, and contractors via e-mail. A total of 870 questionnaires were administrated, out of which 162 were completed.

The main target of this study is to define the critical barriers of CWM on superstructure construction. Therefore, the working area of participants is a significant variable. Most of the participants (64.2%) work on housing projects. Classifying participants according to their education level that most of the participants (64.0%) had a bachelor’s degree. The participants’ experience (in years) in the construction industry is also essential in evaluating the significance of the barriers to CWM. Therefore, the distribution of the respondents’ experience in the construction industry provides a necessary description of the obstacles to CWM. Of the participants, 46.9% had 1-20 years of experience, whereas 37.0% had more than 20 years of experience.

Analyzing the Data

Initially, participant responses were encoded, and various statistical tests, including reliability analysis and normalized mean value assessment, were employed.

Reliability measurement is imperative to gauge internal consistency among survey questions using the Likert scale (Nunnally & Bernstein, 2007). Cronbach’s alpha (α) coefficient served as the metric to evaluate the statistical reliability and validity of participants' responses. The α coefficient ranges from "0" to "1," with the minimum acceptable reliability threshold set at 0.7 (Tavakol & Dennick, 2011).

Identifying the critical barriers to CWM and ranking them constituted a vital objective of this study. Consequently, the mean score ranking method was applied. Additionally, normalized mean values (NMVs) were crucial in determining the criticalities of the 54 barriers to CWM. The calculation of NMVs for each barrier followed Equation 1. A barrier with an NMV surpassing 0.5 was considered a critical barrier (CBs) (Liao & Teo, 2017; Zhou et al., 2019).

$$Normalised\ mean\ value = \frac{(mean\ of\ SC - lowest\ mean)}{(highest\ mean - lowest\ mean)} \quad (1)$$

Findings

To assess the internal consistency of the questionnaire, a reliability analysis was carried out utilizing Cronbach's α coefficient. The α coefficient for the dataset related to the 54 barriers to CWM was calculated to be 0.981, surpassing the minimum threshold of 0.7.

Mean score ranking and normalized mean value analyses were performed on the 54 barriers.

Table 1. Identifying and ranking the CBs to CWM.

Process	Barriers Coded as	Barriers	Mean	SD	NMV	Ranking
Design Process	D1	Frequent design changes	3.62	1.16	0.49	38
	D2	Lack of knowledge of the designer	3.69	1.14	**0.57***	30
	D3	Low quality of design	3.50	1.28	0.35	45
	D4	Failure to observe the standard specified in legal regulations	3.61	1.21	0.48	39
	D5	Poor co-ordination and communication	3.97	1.19	**0.89***	7
	D6	Lack of experience of designer	3.79	1.17	**0.68***	18
	D7	Lack of material knowledge of designer	3.95	1.19	**0.86***	8
	D8	Deficiencies/confusion in agreement documents	3.62	1.15	0.49	37
	D9	Changes in customer demands at the last moment	3.90	1.26	**0.81***	10
	D10	Deficiency in design-related construction details and incompatibility between projects in details	3.91	1.25	**0.82***	9
	D11	Manufacturing in the field is contrary to the project and its annexes	3.88	1.17	**0.78***	13
	D12	Design and detail errors due to lack of information	3.88	1.15	**0.78***	12
Supply Chain	SC1	Material order errors due to lack of coordination between stakeholders	3.79	1.22	**0.68***	21
	SC2	Incorrect estimation of the required amount of material	3.7	1.27	**0.58***	27
	SC3	Purchase of product contrary to specification/ poor material supply	3.78	1.20	**0.67***	22
	SC4	Supplier errors (wrong/incorrect product shipment by the supplier, supplier sending a different product from the requested product)	3.57	1.23	0.43	41
	SC5	Changes in material costs	3.19	1.25	0.00	53
	SC6	Ordering more than required	3.66	1.18	**0.53***	33
	SC7	Frequent order changes	3.45	1.24	0.30	48
Transportation of Material	T1	Damage to material during transport	3.53	1.23	0.39	44
	T2	Problems in entrance of delivery vehicles to the site	3.19	1.21	0.00	54
	T3	Challenges experienced in transportation	3.67	1.21	**0.55***	31
	T4	Unsuitable inefficient material discharge method	3.76	1.21	**0.65***	24
	T5	Careless behavior during material unloading	3.77	1.19	**0.66***	23
	T6	Inadequate protection during material unloading	4.06	1.19	**0.99***	2

Table 1. Identifying and ranking the CBs to CWM (*cont.)*.

Process	Barriers Coded as	Barriers	Mean	SD	NMV	Ranking
Planning and Management	PM1	Lack of a management plan for wastes generated during construction at the site	3.83	1.16	**0.73***	15
	PM2	Incorrect planning for required material quantities	3.67	1.17	**0.55***	32
	PM3	Lack of information about material dimensions	4.02	1.20	**0.94***	5
	PM4	Increased reconstruction works	3.55	1.15	0.41	42
	PM5	Lack of control of the material brought to the construction site	3.80	1.15	**0.69***	17
Material Storage	MS1	Unsuitable field storage area causing damage or deterioration	3.85	1.14	**0.75***	14
	MS2	Incorrect storage methods	3.54	1.20	0.40	43
	MS3	Storage away from the site	3.70	1.19	**0.58***	28
	MS4	Unnecessary amount of wasteful products in the field	3.73	1.18	**0.61***	25
	MS5	Loosely packaged materials supplied	3.73	1.13	**0.61***	26
	MS6	Incorrect transport methods from the storage point to the construction site	3.79	1.13	**0.68***	19
Construction	C1	Mistakes due to carelessness	3.63	1.18	**0.50***	36
	C2	Unused materials and products	3.27	1.13	0.09	51
	C3	Equipment failure	4.05	1.19	**0.98***	3
	C4	Poor workmanship	3.81	1.20	**0.70***	16
	C5	Time pressure	4.02	1.14	**0.94***	4
Human Resources	HR1	Lack of experience employee	3.79	1.16	**0.68***	20
	HR2	Unethical behavior of workers	3.89	1.18	**0.80***	11
	HR3	Lack of education of workers	4.07	1.14	**1.00***	1
	HR4	Lack of qualified workers	3.98	1.14	**0.90***	6
	HR5	Inappropriate over/ misuse of materials	3.65	1.17	**0.52***	35
	HR6	Lack of worker's willingness to work	3.43	1.18	0.27	49
	HR7	Abnormal abrasion of materials	3.70	1.10	**0.58***	29
	HR8	Lack of communication among stakeholders	3.25	1.26	0.07	52
	HR9	Labour overtime work	3.65	1.15	**0.52***	34
	HR10	Cutting of material uneconomical shapes	3.36	1.24	0.19	50
External	E1	Weather conditions	3.58	1.14	0.44	40
	E2	Vandalistic behavior of workers	3.49	1.16	0.34	46
	E3	Damages caused by 3rd parties	3.48	1.15	0.33	47

*: denotes critical barrier. SD: Standard deviation NMV: normalized mean value

The result of NMV analysis revealed that out of the 54 barriers, 36 were identified as CBs, characterized by normalization values equal to or greater than 0.50, concerning CWM in the Turkish construction industry (Table 1).

The top five CBs to CWM were identified as follows:

1. Lack of education of workers (HR3)
2. Inadequate protection during material unloading (T5)
3. Equipment failure (C3)
4. Time pressure (C5)
5. Lack of information about material dimensions (PM3)

Conclusion

This research sought to identify and assess the critical barriers hindering the efficacy of CWM in the Turkish construction industry. Employing an extensive questionnaire survey directed at professionals, including architects, civil engineers, construction site chiefs, and contractors, we obtained significant insights into the difficulties confronted by industry practitioners. Utilizing normalized mean values, the subsequent analysis facilitated the prioritization of the identified barriers.

The results indicate that the pivotal barriers to CWM in the Turkish construction industry are intricate, spanning diverse domains such as human resources, material transportation, construction activities, and project management. The foremost challenge identified was the insufficient education of workers, underscoring the necessity for tailored training initiatives to augment awareness and comprehension of waste management practices. Substantial operational challenges were also recognized in terms of inadequate protection during material unloading and equipment failures, emphasizing the significance of implementing safety protocols and ensuring regular equipment maintenance.

Furthermore, the impact of time pressure on construction projects emerged as a salient barrier, signifying the requisite for enhanced project planning and scheduling that incorporates efficient waste management practices. Additionally, the absence of information regarding material dimensions underscores the crucial role of accurate data in waste sorting and recycling endeavors.

Effectively addressing these critical barriers demands collaborative engagement from stakeholders throughout the construction industry. Initiatives focusing on education should be implemented to bridge the knowledge gap among workers during material handling. Moreover, optimizing project management strategies that integrate waste management considerations into the broader construction timeline can mitigate the challenges of time pressure on effective waste handling.

In conclusion, the insights gleaned from this study offer valuable perspectives for industry professionals, policymakers, and educators to formulate targeted interventions and strategies intended to surmount the identified barriers and foster sustainable construction waste management practices within the Turkish construction industry. By addressing these challenges, the industry can progress toward a more environmentally conscious and resource-efficient future.

References

Abarca-Guerrero, L., Maas, G., & Van Twillert, H. (2017). Barriers and motivations for construction waste reduction practices in Costa Rica. *Resources*, *6*(4), 69.

Ajayi, S. O., Oyedele, L. O., Bilal, M., Akinade, O. O., Alaka, H. A., Owolabi, H. A., & Kadiri, K. O. (2015). Waste effectiveness of the construction industry: understanding the impediments and requisites for improvements. *Resources, Conservation and Recycling*, *102*, 101-112.

Al-Hajj, A., & Hamani, K. (2011). Material waste in the UAE construction industry: main causes and minimization practices. *Architectural Engineering and Design Management*, *7*(4), 221-235.

Aslam, M. S., Huang, B., & Cui, L. (2020). Review of construction and demolition waste management in China and USA. *Journal of Environmental Management*, *264,* 110445.

Doust, K., Battista, G., & Rundle, P. (2021). Front-end construction waste minimization strategies. *Australian Journal of Civil Engineering*, *19*(1), 1-11.

Hasan, M. R., Sagar, M. S. I., & Ray, B. C. (2023). Barriers to improving construction and demolition waste management in Bangladesh. *International Journal of Construction Management*, *23*(14), 2333-2347.

Liao, L., & Teo, E. A. L. (2017). Critical success factors for enhancing the building information modelling implementation in building projects in Singapore. *Journal of Civil Engineering and Management*, *23*(8), 1029-1044.

Liberati, A., Altman, D. G., Tetzlaff, J., Mulrow, C., Gøtzsche, P. C., Ioannidis, J. P., & Moher, D. (2009). The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration. *Annals of Internal Medicine*, *151*(4), W-65.

Macpherson, A., & Jones, O. (2010). Strategies for the development of International Journal of Management Reviews. *International Journal of Management Reviews*, *12*(2), 107-113.

Nawaz, A., Chen, J., & Su, X. (2023). Factors in critical management practices for construction projects waste predictors to C&DW minimization and maximization. *Journal of King Saud University-Science, 35*(2), 102512.

Nunnally, J.C., & Bernstein, I. H. (2007). *Psychometric theory*. McGraw-Hill.

Polat, G., Damci, A., Turkoglu, H., & Gurgun, A. P. (2017). Identification of root causes of construction and demolition (C&D) waste: the case of Turkey. *Procedia Engineering*, *196*, 948-955.

Reid, J. M., Hassan, K. E. G., & Al-Kuwari, M. B. S. (2016). Improving the management of construction waste in Qatar. *Proceedings of the Institution of Civil Engineers-Waste and Resource Management*, *169*(1), 21-29.

Tavakol, M., & Dennick, R. (2011). Making sense of Cronbach's alpha. *International Journal of Medical Education*, *2,* 53.

Ulubeyli, S., Arslan, V., & Kazaz, A. (2018). Construction and demolition waste recycling plants in Turkey. *Proceedings of the 4th International Conference on Engineering and Natural Science*, Ukraine, pp. 476-482.

Yang, B., Song, X., Yuan, H., & Zuo, J. (2020). A model for investigating construction workers' waste reduction behaviors. *Journal of Cleaner Production*, *265*, 121841.

Yu, R., Ostwald, M. J., Gu, N., Skates, H., & Feast, S. (2022). Evaluating the effectiveness of online teaching in architecture courses. *Architectural Science Review*, *65*(2), 89-100.

Zhou, Y., Yang, Y., & Yang, J. B. (2019). Barriers to BIM implementation strategies in China. *Engineering, Construction and Architectural Management*, *26*(3), 554-574.

Retrofitting Conventional Residential Buildings Towards Nearly Zero Energy Buildings

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Abstract

The urgent requirement to mitigate the effects of climate change and decrease greenhouse gas emissions has encouraged a worldwide demand for environmentally friendly building methods. concerning this issue, Türkiye, especially Izmir, has made substantial progress toward Nearly Zero Energy Buildings (NZEBs). Many existing residential buildings in Izmir, Türkiye, are conventional buildings. Thus, conventional residential buildings in Izmir should be retrofitted to decrease their energy consumption and carbon emissions production. Sustainable retrofitting of conventional residential buildings is a critical approach to accomplishing the NZEBs target by 2050. Therefore, this study aims to explore and highlight sustainable retrofitting strategies that can be used to achieve NZEBs status in residential buildings in Izmir, Türkiye. A case study addressing a conventional residential building in Izmir was performed to fulfill the research objective. This case study building was simulated in DesignBuilder to understand the impact of applying different retrofit measurements. The results reveal that all scenarios lowered the building's overall energy consumption to 54%. Further, a mixed scenario can save significant energy in Izmir's Mediterranean climate. The results of this study could promote the adoption of sustainable retrofitting methods and lead practitioners in the architecture, engineering, and construction (AEC) industry in how to retrofit conventional residential buildings in the Mediterranean climate sustainably. The sustainable retrofitting approaches discussed in this study can be used in the AEC industry to help the government meet its ambitious NZEB goal of reducing carbon emissions by 2050. Also, this approach can be a guideline for residential buildings to minimize CO_2 emissions by reducing energy consumption and increasing the durability of buildings in climates similar to the Izmir climate.

Keywords: *building energy simulation, energy efficiency, nearly-zero energy buildings (NZEB), residential building, retrofitting.*

Introduction

In Türkiye, several research has been conducted to minimize building energy usage (Jaysawal et al., 2022; Colclough et al., 2024). The data depicts that Türkiye's energy consumption has grown in all industries since 1990. From 2008 to 2020, residential energy consumption rose by 12%. Although residential buildings' energy consumption in 2021 is lower than that of industry and transportation, it is still on an increasing path that should be regulated by lowering energy consumption (IEA, International Energy Agency).To meet the Paris Agreement's goals, Türkiye must reduce emissions by 40% by 2030 (IEA, International Energy Agency). Turkey's National

Energy Plan (2022) now only aims to achieve nearly zero emissions by 2053 (Türkiye National Energy Plan, 2022). Türkiye has considerable potential for enhanced energy efficiency, improving the quality of life in big cities such as Izmir. However, in Türkiye, there has been limited emphasis on research activities dedicated to retrofitting existing buildings to meet the target of NZEBs (nearly zero energy buildings). Acar et al. (2022), proposed a complete design method for achieving NZEB from the outset to construction. They incorporated renewable energy technology, such as solar panels and wind turbines, into their building energy plan. Acar and Kaska found that for hot semi-arid climates, Mediterranean climates, and cold semi-arid climates, respectively, NZEB designs with additional energy of up to 23 kWh/sqm, 9 kWh/sqm, and 3 kWh/sqm were obtained (Acar et al., 2022). Hajizadeh et al. (2023) conducted studies in Türkiye to improve residential buildings in Antalya, Türkiye, to minimize energy consumption and CO_2 emissions, thus contributing to NZEBs. Researchers could decrease the building's overall energy use by 58% in this study (Hajizadeh et al., 2023). To contribute to the NZEBs literature in Türkiye, this study aims to explore and highlight a sustainable retrofitting strategy that can be used to achieve NZEBs status in residential buildings in Izmir, Türkiye.

Methodology

This study assesses energy use and carbon dioxide emissions before and after retrofitting the existing residential building. The first step was defining a residential building in Izmir as a case study, a conventional building throughout Türkiye. Izmir is a city on Türkiye's Aegean coastline. Izmir has a Mediterranean climate, with hot, dry summers and warm, rainy winters. Summers in Izmir are often warm, particularly in July and August, with high temperatures that frequently approach 30 degrees Celsius. Winters in Izmir are mild, with temperatures seldom falling below freezing and occasional rains. Spring and fall in Izmir provide mild temperatures. The Turkish standard "TS 825" climate classification was used to select the representative city. In TS825, climate zones are classified based on degree days (Dino et al., 2019).

The RB has three floors, each with a single unit at 63.46sqm area and 3m height, which includes two bedrooms, one bathroom, one restroom, one kitchen, and one living room. The building's orientation is north south. This case study's total yearly energy usage is 76.75 kWh/sqm. The geometric information of RB in Türkiye and NZEB measures is shown in Table 1. Table 1 lists RB's base characteristics and methods for achieving maximum energy efficiency. These include energy-efficient lighting, generating electricity, well-insulated, airtight building envelope, high-performance windows, and installing PV panels (Dino et al., 2019; Serghides et al., 2017). Table 2 shows the characteristics of the RB energy system.

Table 1. Geometric information of RB and NZEB measures.

	Properties	Characteristics	Measures for NZEB
1	Latitude	38.4237°N	-
2	Longitude	27.1428° E	-
3	Orientation	0◦	-
4	Shape	Rectangular (12 m × 10 m)	-
5	Floor height	3 m height	-
6	Roof U-value	U =1 W/sqm K	U = 0.2W/sqm K with radiant barrier(Serghides et al. 2017)
7	Wall U-value	U = 2 W/sqm K (no radiant barrier)	U = 0.4W/sqm K with radiant barrier(Serghides et al. 2017)

8	Operable shading	Operable window without exterior shading	Venetian blinds close if the sun on the window and the indoor temp above comfort (Dino et al. 2019)
9	Infiltration	1.5 ACH	0.6 ACH (Dino et al. 2019)
10	PV system	None	Monocrystalline(Dino et al. 2019)

Table 2. The characteristics of the building's energy system.

	System	Description	System Fuel
Heating system	Heating Equipment	Radiator heating, Boiler HW, Nat Vent	Natural Gas
	DHW System	heating, Boiler	Natural Gas
Cooling system	Cooling System	Natural (Through Openings)	-
Lighting system	Lighting System	100% Compact Fluorescent Lamp (CFL)	Electricity

The second step consisted of conducting an energy analysis for the RB via DesignBuilder energy modelling software (Figure 1). DesignBuilder and PVSOL® premium 2023 software were used for modelling. The RB's windows are single-pane glass with an aluminium frame and no shading components, and the lighting fixtures are compact fluorescent lights (CFL); the RB's energy performance is inadequate. Furthermore, insufficient wall insulation led to more heat escaping in the winter and less heat entering the summer. As a result, annual end-use energy consumption is rather substantial. Five scenarios were applied to the RB in the third stage to enhance building energy performance and reduce CO_2 emissions. The heating system was designed as a central system with radiators in each room. The heating boiler uses natural gas. Natural ventilation was used to provide cooling. DHW was also prepared using a natural gas boiler. All simulations ran for a year.

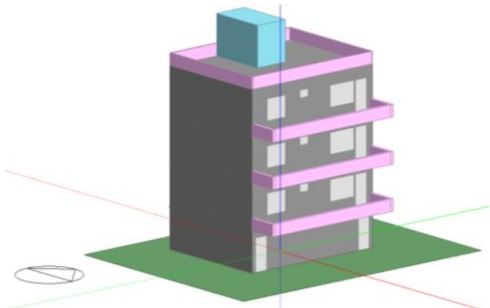

Figure 1: Building 3D-model in DesignBuilder.

Results and Discussions

After analysing the energy consumption in the RB in Izmir, it was discovered that most energy expenditure is linked to electricity usage. The annual energy consumption of RB is 12.40 MWh, which comprises 7235.98 kWh of electricity, 5170.16 kWh of natural gas, 477.30 kWh for interior lighting, and CO_2 emissions of 5354.71 kg. To achieve the NZEB goal, a scenario that may substantially decrease electrical consumption is required. This aim may be met by effectively implementing energy-efficient technology and behavioural changes such as integrating LED lighting systems and implementing renewable energy sources like solar panels.

The model was calibrated by comparing annual energy consumption data analysis from reliable sources, such as peer-reviewed articles and established databases. According to M. A. Umbark et al. (2020), a building of 153sqm has an annual energy consumption of 90 kWh/sqm, whereas one of 191sqm has a yearly energy consumption of 69 kWh/sqm in Türkiye. The average annual energy usage in Türkiye for buildings ranging from 153 to 191 square meters is 80 kilowatt hours per square meter (Umbark et al., 2020). Hajizadeh and Seyis (2023) investigated a residential building in Antalya, Türkiye, with a yearly energy usage of 70 kWh/sqm (Hajizadeh et al., 2023) In this research, the RB has an area of 161.63sqm and annual energy consumption of 76.75 kWh/sqm. The Umbark and Hajizadeh publications were used to calibrate the study. Five scenarios were simulated to increase energy efficiency and develop an NZEB in this study.

Sc1_Replacing window: The primary objective of the first scenario is to enhance the building envelope, specifically by replacing windows. This involves the installation of energy-efficient windows characterized by low U-values and high solar heat gain coefficients. The aim is to optimize natural lighting while minimizing heat transfer within the building. Double-glazed windows provide better insulation and reduce electricity and gas use. Therefore, double-glazed windows contribute to better energy efficiency and comfort within buildings by decreasing heat loss during colder months and lowering heat gain in hot seasons. Furthermore, they assist in reducing condensation and noise transmission, improving the overall quality and sustainability of the built environment. In Scenario 1, the double-glazed window LoE (e2=.1) Clr 6mm/13 mm Argon filled and a UPVC frame with 1.493 W/sqm -k U value is replaced with a single-glazed window. Figure 2 shows that in RB, the internal surface temperature was 4.89 °C and after replacing the single-paned window with a double-paned window, the internal surface temperature improved to 12.77 0.89 °C. The heat gained through glazing decreases from -0.16 kW to -0.05 kW after applying Sc1.

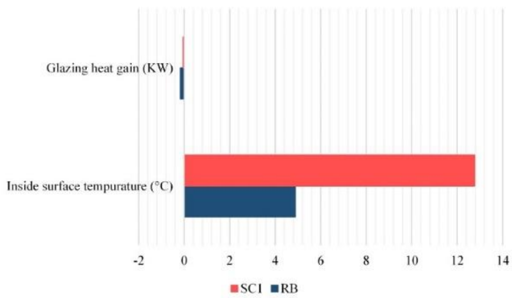

Figure 2: Thermal comfort.

Sc2_Photovoltaic panels: As renewable energy sources, photovoltaic panels were the determined solution for this research. It is presumed that photovoltaic panels are positioned on the building's roof. The IEA Nearly Zero Emissions scenario suggests that solar Energy should account for 41% of global electricity generation by 2030, up from 12% in 2022 (IEA, International Energy Agency). This study simulated 20 photovoltaic monocrystalline solar panels with module dimensions of 1721 mm x 1133 mm x 30 mm and 34 degrees with PVSOL® premium 2023 software (Table 4). Izmir's optimal tilt angle and maximum sun radiation are 34 degrees throughout the year and season (Kacira et al., 2004). Moreover, Figure 3 illustrates the power conversion of solar radiation into electrical Energy, which is -40.13 kWh/sqm. To contribute to meeting the NZEB goal in a Mediterranean environment, implementing PV panels in this case study may produce 48% of the annual electricity demand.

Table 4. Results of 20 PV applications in the case study apartment.

Number of modules	20
Inclination	34 degrees
Model	monocrystalline solar panels
Dimension	1721 mm x 1133 mm x 30 mm
PV modules	20 * AE400MD-108BD (v2)
PV generator surface area	39.1 sqm
Performance ratio	78.2%
PV generator output	8kWp
Specific annual yield (kWh/kWp)	1606.99 kWh/kWp
Cell type	Gallium-doped Mono c-Si PERC, Half-cut cells, 182 mm
Nominal Max. Power	400

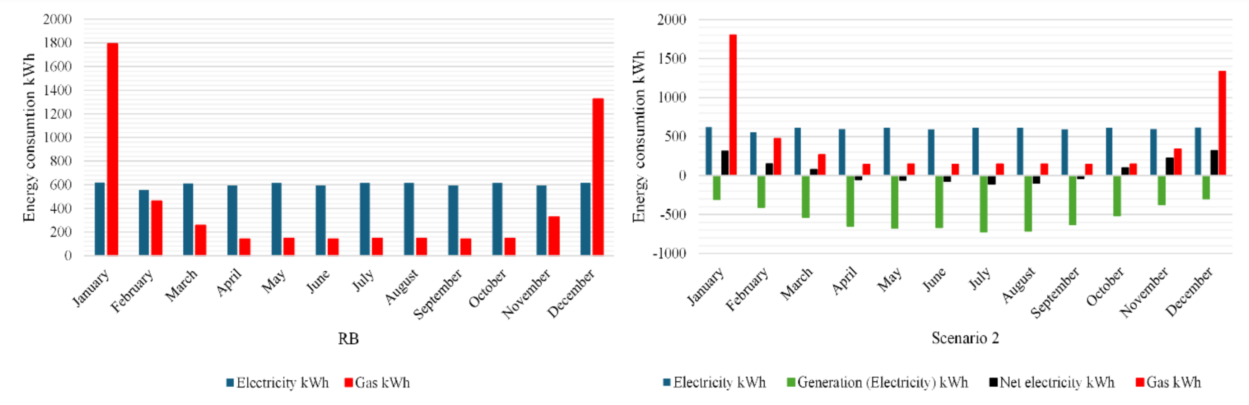

Figure 3: Fuel breakdown of Sc2 and RB by PV panel.

Sc3_Energy-Efficient Lighting: There are several benefits to upgrading lighting systems with light-emitting diode (LED) lights instead of fluorescent lamps. LED lighting uses significantly less Energy than fluorescent lighting, which lowers electrical expenses and saves Energy. Long-term operating expenses are decreased by LEDs' extended lifespan and less requirement for maintenance and replacement. Furthermore, unlike compact fluorescent lights, LEDs generate light more evenly and effectively, improving lighting and lowering glare (Hajizadeh et al., 2023). In addition, LEDs are safer to dispose of and less harmful to the environment than fluorescent lights since they don't contain mercury or other dangerous compounds. Upgrading with LED lighting increases environmental sustainability, lowers maintenance costs, improves illumination quality, and maximizes energy efficiency. For this reason, in Scenario 3, LED fixtures have replaced compact fluorescent lights. The result is a 24% decrease in the annual lighting value from 477.3 kWh in the RB to 361.59 kWh in Sc3.

Sc4_External wall insulation: External wall insulation (EWI) is a very efficient retrofit solution for increasing the energy efficiency of buildings. By applying insulating material to the exterior walls of a building, EWI helps to minimize heat loss, improve thermal comfort, and reduce the consumption of Energy. Expanded polystyrene insulation (EPS) was chosen according to TS825 with a recommended Umax of 0,70 W/sqmK for the external wall in Izmir (Dino et al., 2019; Dilmac et al., 2003). Therefore, EPS insulation with a thermal conductivity of 0.0350 W/m-k and 0.1500 sqm-k/W thermal resistance is intended for insulating external walls to reduce energy consumption with 0.1m thickness. The annual energy consumption of Sc4 is reduced to 11.6 MWh, compared to 12.4 MWh in RB. The heat loss of the wall in Sc4 decreases from -1.67 KW to -1.29 KW, indicating that the wall has become better insulated or that steps have been taken to limit heat flow through the wall.

Sc5_Combination scenario: In scenario 5, implementing a comprehensive retrofit strategy that includes elements such as LED lighting replacement, double-glazed window installation, external wall insulation, and PV panels results in a highly efficient retrofit solution that improves energy performance by more than 54% on the way to achieving NZEB standards in Izmir shown in Tables 5 and 6. Replacing compact fluorescent lights with energy-efficient LEDs results in a considerable decrease in power usage. At the same time, double-glazed windows improve thermal comfort and minimize heating and cooling needs. Furthermore, external wall insulation is essential for reducing heat loss and increasing energy efficiency. The combined scenario outcome is the most effective one, with an impressive 54% increase in energy usage. Table 5 shows a complete summary of construction details for scenarios before and after retrofitting. According to Table 6, the most effective scenario is the installation of PV panels in the Izmir climate. The outcome of scenario 5, indicating a reduction in energy consumption of over 54%, demonstrates alignment with Türkiye's Regulations on Energy Performance in Buildings.

Table 5. Construction details of scenarios before and after retrofitting.

Baseline	**Scenario code**	**Construction**	**Before retrofitting**	**After retrofitting**
			Material	**Material**
Building envelope	Sc1	Window	Single glazing, clear, no shading with Aluminium frame	Dbl LoE (e2=.1) Clr 6mm/13mm Arg, with UPVC frame U value: 1.493 W/sqmk
	Sc4	External Wall	Interior Plaster, Brick, Exterior, Plaster, Insulation, Exterior Plaster	EPS Expanded Polystyrene. R-Value: 0.1500 (sqm -K/W U-value =0.70 W/sqmK[1] (Dilmac et al. 2003)
RES	Sc2	PV panels	-	20 monocrystalline silicon with 34 degrees
Energy-efficient lighting	Sc3	Lighting	CFL, Normalized power density: 5.00 (W/sqm -100 lux)	LED Normalized power density:2.5 (W/sqm - 100 lux)
Combine scenario	Sc5	Building envelope, RES, Lighting		Sc1, Sc2, Sc3, Sc4

Table 6. Summary of the results of RB and scenarios.

	Electricity	Natural Gas	Interior Lighting	On-Site Electric Sources	CO_2	Improvement
	[kWh]	[kWh]	[kWh]	[kWh]	[kg]	[%]
RB	7235.98	5170.16	477.3	0	5354.71	-
Scenario 1	7233.06	3746.37	477.3	0	5085.9	12%
Scenario 2	749.307	5224.38	477.3	6486.873	1433.96	52%
Scenario 3	7120.36	5199.02	361.59	0	5290.06	1%
Scenario 4	6855.87	4772.92	449.2	0	5049.86	6%

[1] Maximum U-values allowed by the current Turkish code (TS825 standard) for climatic code 1.

Scenario 5	633.707	5259.36	361.59	6486.873	1370.47	54%

Figure 4 depicts the CO_2 emissions amount for the RB and various scenarios. Figure 4 shows that CO_2 emissions in scenario 2 are minus from April to August, and in scenario 5, emissions are minus from April to September. Negative carbon refers to a building with nearly zero emissions, as it is impossible to release negative amounts of carbon. PV panels and combination scenarios have the lowest carbon emissions, contributing to CO_2 reduction.

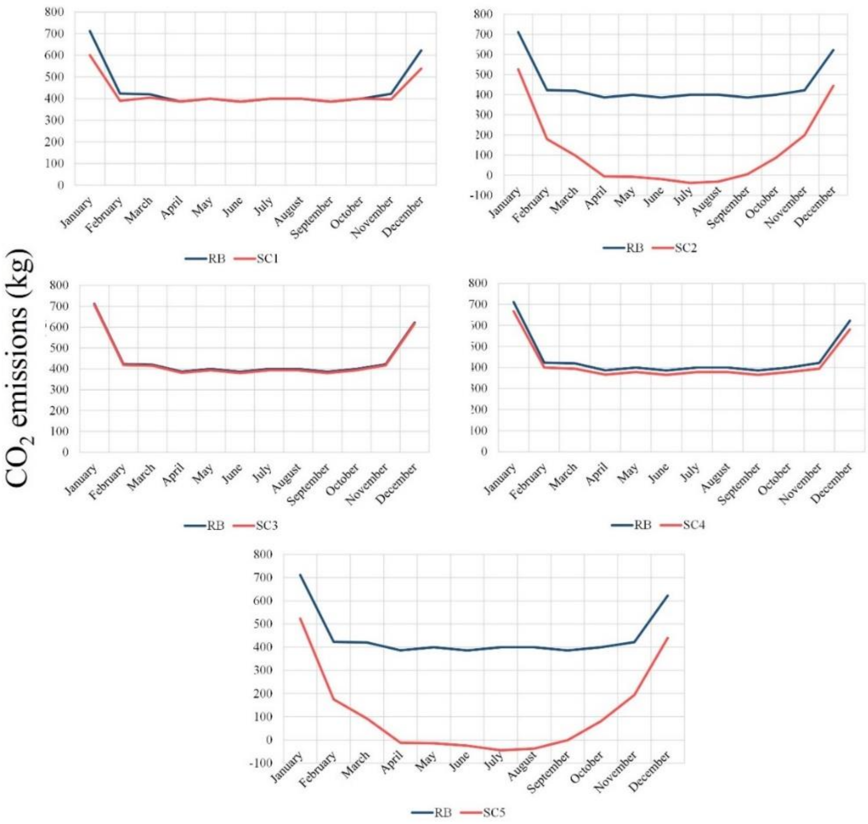

Figure 4: Comparison between the different scenarios and RB regarding CO_2 emissions.

Conclusion

This study proposes five distinctive scenarios for achieving the NZEB goal in Izmir and providing a solution for Türkiye's Mediterranean climate. Recognizing the distinct challenges and possibilities of specific geographical environments, each scenario offers a detailed approach to energy retrofitting, considering building design, climatic conditions, and available resources. The case study building was designed using DesignBuilder and PVSOL® Premium 2023. The scenarios include replacing single-glazed windows with double-glazed, replacing compact fluorescent lamps with LED lamps, additional insulation of the external wall with EPS, implementing PV panels on top of the roof, and combining all the above scenarios. An analysis of all results emphasizes the importance of implementing photovoltaic panels in residential buildings in Mediterranean conditions since they can generate more than 52% of the building's electrical consumption. The RB's overall consumption of Energy was 12.4 MWh. Retrofitting scenario 1, including window replacements, reduces overall energy usage to 10.97 MWh.

scenario 2, which included installing 20 photovoltaic panels, resulted in the most significant reduction, with total energy usage lowering to 5.91 MWh. Scenario 3 resulted in a slight decrease in energy usage to 12.31 MWh after upgrading lighting fixtures. Scenario 4 focused on applying external wall EPS insulation, resulting in a total energy usage of 11.62 MWh. Furthermore, the combination scenario, scenario 5, achieved the most promising results, with a total energy consumption of 5.88 MWh, demonstrating the potential for considerable energy savings through integrated retrofit solutions. These findings show the necessity of specialized retrofitting solutions in achieving significant reductions in energy usage and meeting the NZEB goal by 2050. The sustainable retrofit approaches may benefit residential buildings by reducing energy consumption, boosting property value, minimizing CO_2 emissions, and increasing building durability in the Izmir climate. These five scenarios can be employed in the AEC industry to accomplish the NZEB goal of lowering carbon emissions by 2050. Additionally, a lack of official research on NZEB standards in Türkiye indicates that this area remains under investigation. Future research could investigate changing the tilt angles and materials of PV panels to increase energy efficiency. This approach would provide valuable insights into maximizing energy generation potential and incorporating various materials and combinations into successful energy scenarios for sustainable building practices.

References

Acar, U., & Kaska, O. (2022). Energy and economical optimal of Nzeb design under different climate conditions of Türkiye. *Journal of Building Engineering, 60*, 105103.

Colclough, S., & Salaris, C. (2024). Quantifying overheating in nZEB Irish residential buildings: an analysis of recorded interior temperatures of Irish newbuild and retrofit residential buildings against CIBSE, Passive House and WHO overheating criteria and recorded occupant satisfaction. *Energy and Buildings, 303*, 113571.

Dilmac, S., & Kesen, N. (2003). A comparison of new Turkish thermal insulation standard (TS 825), ISO 9164, EN 832 and German regulation. *Energy and Buildings, 35*(2), 161-174.

Dino, I. G., & Meral Akgül, C. (2019). Impact of climate change on the existing residential building stock in Turkey: an analysis on energy use, greenhouse gas emissions and occupant comfort. *Renewable Energy, 141*, 828-846.

IEA (International Energy Agency) (2023). *Net zero by 2050 - a roadmap for the global energy sector*. https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf.

Jaysawal, R. K., Chakraborty, S., Elangovan, D., & Padmanaban, S. (2022). Concept of net zero energy buildings (NZEB) - a literature review. *Cleaner Engineering and Technology, 11*, 100582.

Kacira, M., Simsek, M., Babur, Y., & Demirkol, S. (2004). Determining optimum tilt angles and orientations of photovoltaic panels in Sanliurfa, Turkey. *Renewable Energy, 29*(8), 1265-1275.

Hajizadeh, S., & Seyis, S. (2023). Retrofit strategies for a nearly-zero energy residential building: A case study in Antalya, Türkiye.

Serghides, D. K., Dimitriou, S. D., Michaelidou, M., Christofi, M., & Katafygiotou, M. (2017). Achieving nearly zero energy multi-family houses in Cyprus through energy refurbishments. *IEEE*, *5*(1), 19-28.

Türkiye National Energy Plan (2022). *Türkiye_National_Energy_Plan*. https://enerji.gov.tr/Media/Dizin/EIGM/tr/Raporlar/TUEP/T%C3%BCrkiye_National_Energy_Plan.pdf, zuletzt geprüft am 20.01.2024.

Umbark, M. A., Alghoul, S. K., & Dekam, E. I. (2020). Energy consumption in residential buildings: comparison between three different building styles. *Sustainable Development Research Journal*, *2*(1), 1.

Corporate Sustainability Report Trends in Construction Companies

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Abstract

Corporate sustainability defines as the reflection of sustainability at the company level. Corporate sustainable companies are expected to gain competitive advantage through public awareness. Therefore, companies try to legitimize their corporate sustainability in the eyes of the public and stakeholders: For this purpose, corporate sustainability reports are commonly used. The main purpose of this study is to identify the main trends and tendencies by performing a systematic content analysis aiming to reveal the corporate sustainability trends and differences of the construction companies included in the ENR 2022 (Engineering news-record) "Top 250 Global Contractors" list. The content analysis is based on the "Corporate Sustainability-GRI (Global Reporting Initiative) Reports" published annually by the construction companies. The reports of the companies were analyzed in terms of factors such as the sustainability dimensions they give importance in their corporate sustainability, their sustainability practices, the topics they priorities in sustainable development and their governance structures. As a result of the content analysis, the differences and changes in the corporate sustainability approaches of the construction companies were evaluated according to years. In this way, it is aimed to reveal the impact and role of reports on companies' corporate sustainability commitment.

Keywords: *construction companies, corporate sustainability, GRI, sustainability reports.*

Introduction

The concept of sustainability was first mentioned in the 1960s. The concept is defined as a participation process that focuses on the responsible use of all of society's social, cultural, scientific, natural and human resources and offers a social perspective on the basis of respecting this (Gladwin et al., 1995). Sustainability can only be achieved for countries and organizations if it is achieved in economic, social and environmental dimensions and holistically (Şahin et al., 2018). Sustainable development is defined in the Brundtland Report of the World Commission on Environmental and Development (WCED) as "development that meets the needs of the present generation without jeopardizing the needs of future generations" (Brundtland, 1987). From a macro perspective, the definition focuses on balancing the needs of the present generation with the needs of future generations, while from a micro perspective, it focuses on the sustainable development of national economies and thus businesses (Aktaş et al., 2013). According to this perspective, in addition to financial responsibilities such as revenue generation and profitability, businesses also have responsibilities concerning society and the environment. The concept that expresses these new responsibilities of businesses and approaches sustainable development goals from a business perspective is corporate sustainability (Aktaş et al., 2013). Corporate sustainability performance has changed traditional management processes by focusing not only on financial aspects of business performance but also on social and environmental dimensions (Laskar & Maji, 2016).

The need to convey information to stakeholders on whether the responsibilities imposed on businesses have been fulfilled, has required businesses to make disclosures about their sustainability activities, measure and report their performance (Aktaş et al., 2013). Global non-profit organizations and initiatives have established guidelines, principles and standards that guide businesses on how to report. However, the lack of any legal obligation in this regard causes differences in the content and scope of the reports, especially the publication periods.

In this study, which examines the sustainability reports published in the selected production companies, it is aimed to reveal the similarities and differences in the content of the reports. For this purpose, content analysis was applied to the sustainability reports published by 5 large-scale Turkish production companies in the ENR 250 list between 2018 and 2022. In the first part of the study, the status of corporate sustainability in the construction sector and the scope and content of the reporting frameworks and indices used are discussed. Then, the sustainability reports used by companies to legitimize their corporate sustainability are comparatively analyzed through content analysis.

Corporate Sustainability in Construction Companies

According to the definition of sustainability in the Brundtland Report (1987), "Sustainable development is development that responds to the needs of the present without compromising the ability of future generations to respond to their own needs". WCED defines sustainability from a holistic and comprehensive perspective, encompassing the interconnected and interdependent economic, environmental and social spheres (Brundtland, 1987). At the business level, Dyllick and Hockerts (2002) define sustainable development as "responding to the needs of a firm's direct and indirect stakeholders without compromising its ability to meet the needs of future stakeholders" (Zuo et al., 2013). In other words, sustainability is considered as "Sustainable Development (SD)" at the global level and "Corporate Sustainability (CS)" at the business level (Figure 1).

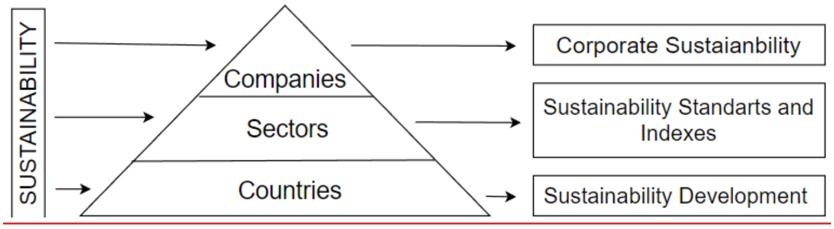

Figure 1: Corporate sustainability and sustainable development.

Corporate Sustainability is defined as a business approach that creates long-term shareholder value by embracing opportunities and managing risks arising from economic, environmental and social developments (Dow Jones Sustainability Index, 2012). The key to understanding Corporate Sustainability is to examine the variables in these three dimensions (Figure 2). The environmental dimension focuses on sustaining natural capital in the global ecosystem, while the social dimension aims to create equality of opportunity and meet the basic human needs of current and future generations. The economic dimension involves long-term value creation (Ludwig & Sassen, 2022)

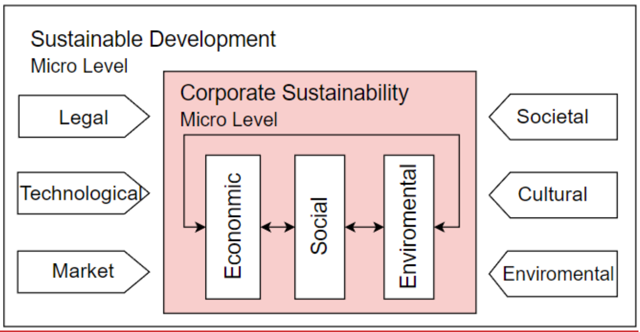

Figure 2: Dimensions of corporate sustaianability (Baumgartner & Ebner, 2010).

As construction sector includes many different variables, it requires being open to change in sustainability issues such as climate change and social development. In this case, the relationship between sustainability and corporate strategy is of great importance (Türker, 2021). The impact of the construction industry on sustainable development is not only related to environmental issues such as climate change, resources and land use, but also to social issues and societal impacts such as the built environment affecting human activities. Pitt et al. (2009) state that 'the built environment affects all human activities'. In other words, the social, environmental and economic dimensions of sustainability also valid when it follows up on corporate sustainability of companies in the construction industry. Therefore, construction companies have to balance commercial drivers with the demands for high-profile sustainable buildings and enhanced corporate sustainability (Glass, 2012). These impacts and societal expectations encourage firms to address and report on the contribution of their activities to sustainable development (SD) (Cortés et al., 2023).

Sustainability Reports in Construction Companies

Sustainability reporting involves disclosing non-financial information about business activities to internal and external stakeholders, aligning with sustainable development goals for measuring corporate performance. These reports help organizations understand the connection between their values, management models, strategies, and the global sustainable economy. By assessing economic, environmental, and social performance, sustainability reporting assists organizations in setting appropriate goals and managing change effectively (Kocamiş & Yildirim, 2016). Its core purpose is to showcase companies' commitments and accomplishments across all sustainability aspects from stakeholders' viewpoints (Zuo et al., 2012).

Sustainability reports are disclosed to stakeholders as the results of the company's corporate sustainability performance in accordance with strategic priorities (Figure 3). Various reasons drive businesses to engage in sustainable reporting, ranging from instrumental to strategic motives such as enhancing competitiveness, expanding business operations, fostering growth, building long-term partnerships, achieving cost savings, streamlining project management, and enhancing communication. Strategic motives prominently include collaboration with stakeholders and broadening the customer base (Cortés et al., 2023).

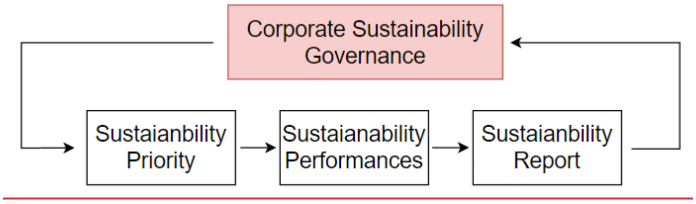

Figure 3: The correlation between corporate sustainability and reporting.

Common issues and themes related to sustainability in the construction industry include lack of customer support for sustainable initiatives, with cost and time being primary performance criteria. Sustainability practices are often compliance-oriented, and the level of corporate sustainability implementation is tied to profitability. Corporate sustainability implementation is still in its early stages (Afzal & Lim, 2022).

On the other hand, it is observed that company managers influence reporting, and companies with professional network managers demonstrate higher reporting quality (Luo & Liu, 2020). Internal factors, like rewards and corporate culture, can also impact sustainability practices and reporting, in addition to external factors (Zhang et al., 2022). In addition to country-specific conditions, other factors like internationalization and size also influence reporting practices (Cortés et al., 2023). In other words, there are significant variations in the content and extent of sustainability reports among construction firms.

The literature depicts the current state of SR in the construction sector. The industry trails the global SR trend, lacking a uniform reporting approach, common definitions, criteria, and agreement on reported indicators. It also lacks clear materiality determination processes, stakeholder engagement, and awareness of reporting standards (Glass, 2012). However, firms' performance measurement is mostly based on financial indicators. Ranking systems such as Engineering News Record's (ENR) list of top construction companies are based solely on gross revenues.

In contrast, some construction firms report their corporate sustainability performance and are included in sustainability indices such as the Borsa Istanbul Sustainability Index (BIST100) and the Dow Jones Sustainability Index (DJSI). In order to be included in these indices, companies mainly report according to the guidelines created by the Global Reporting Initiative. In addition to the GRI guidelines, the United Nations Global Compact (UNGC), Integrated Reporting (IR) and Carbon Disclosure Project (CDP) reports are also among the main reporting frameworks. Commonly used reporting frameworks are given in (Table 1).

Table 1. Sustainability report frameworks.

Framework	Council	
G4	Global Report Initiative (GRI)	It reveals the sustainability status with social, environmental and economic dimensions. Measures with performance indicators for these dimensions.
COP	United Nation Global Compact (UNGC)	Handles the 10 critical human rights issues of the UNGC. Correlates 10 principles with business activities. Published annually
IR	International Integrated Reporting Council – (IIRC)	Integrated reporting establishes the link between the organization's strategy and sustainability. It guides the vision with information from the past.
CDP	Carbon Disclosure Project (CDP)	The reporting topics are all environmental. CDP is a source of international environmental data.

Source: http://www.borsaistanbul.com/data/kilavuzlar/surdurulebilirlik-rehberi.pdf

The most popular reporting frameworks adopted by construction organizations are the Global Reporting Initiative (GRI); Dow Jones Sustainability Index and ISO 26000 (Afzal et al., 2017). reporting frameworks and their focal points are presented in Table 2. The GRI guidelines are widely used guidelines for creating sustainability reports and analyzing firms' sustainability performance, helping firms to maintain their legitimacy (Pérez-Batres et al., 2011).

Table 2. Sustainability reporting guidelines and audits.

	Year of launch	Focus	Certification system	Construction Industry specific	
GRI	2000	Social, Environmental, Economic	No	Yes	Guideline
ISO26000	2010	Social	No	No	Standards
ISO14001	1996	Environmental	Yes	No	Standards
DJSI	2012	Social, -Environmental, -Economic	No	Yes	Indexes
BIST100	2014	Social, Environmental, Governance	No	Yes	Indexes
FTSE4GOOD	2001	Social, -Environmental, Governance	No	No	Indexes
SA8000	1997	Social	Yes	No	Standards
CDP	2000	Environmental	No	Yes	Guideline

GRI reports include 2 disclosure types: general and specific. General Standard Disclosures focus on strategy and risk and are divided into seven main headings. Specific Standard

Disclosures are divided into indicators and disclosures about the management approach (DMA). Indicators are divided into three parts: social, environmental and economic indicators. Organizations can take these indicators as pure indicators or derive specific indicators related to their business activities. The characteristics of the indicator types specified in the GRI Reporting Format are as follows (Bülbüloğlu, 2018):

- Economic Indicators: This is the total economic impact of the organization on society. It addresses economic impacts on customers, suppliers, employees, providers of capital and the public sector.
- Environmental Indicators: The contribution of the organization to the natural habitat. addresses issues such as resource use, waste management, environmental and health risks, biodiversity
- Social Indicators: It expresses the contribution of the institution/organization to social life and addresses issues such as working conditions, human rights and equality (Aksu, 2016).

The GRI guidelines consist of principles for determining report content and ensuring the quality of the information reported. These principles consist of Reporting Principles, Reporting Guidelines and Standard Disclosures (including Performance Indicators). These elements are considered to have equal weight and importance. Principles for determining report content: prioritization, stakeholder engagement, sustainability framework, completeness. The principles for ensuring report quality are: balance, clarity, accuracy, timeliness, comparability and reliability.

Methodology

In this study, the elements of corporate sustainability reports are discussed and the sustainability reports of the construction companies publishing these reports in Turkey are analyzed on the basis of these criteria. The sample of the study includes the sustainability reports published on the websites of five international construction companies listed in the ENR 250 list and ranked in the top 40 in 2022. In the research, the reporting period is restricted to 2018-2023, covering the last 5 years. Because the reports are currently published on a voluntary platform and therefore there is no common network to access the reports, the reports were accessed from the official websites of the companies. The methodology of the research is summarized in Figure 3.

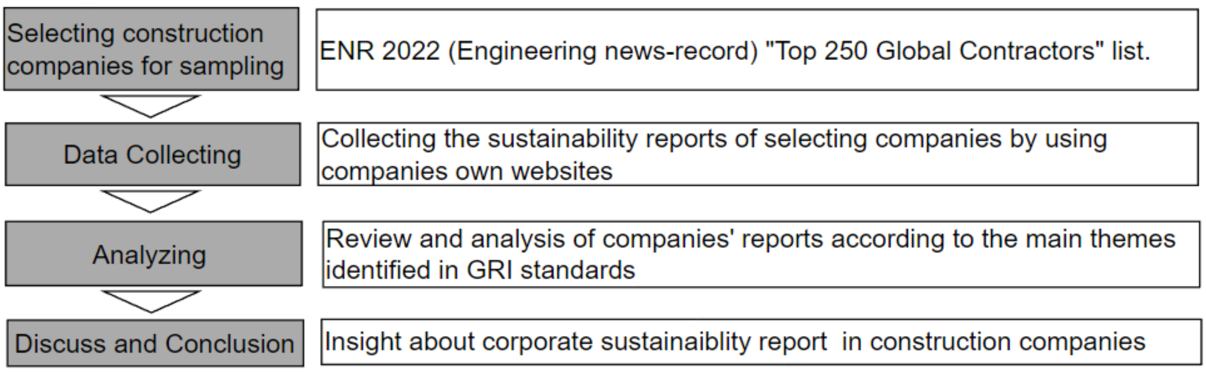

Figure 3: The correlation between corporate sustainability and reporting.

In the review, sustainability reports of 5 construction companies were analyzed based on the sustainability indicators of the commonly used GRI guideline. As the companies publish the reports voluntarily, there may be differences in reporting periods. The reports were analyzed based on the most recently published common report year, 2022, based on the specified themes. Table 3 provides details of the activity fields and the profiles of the companies selected for the survey.

Table 3. Company profiles.

Company Name	Fields of Activity	Activity in the sector (year)	Employee Number
Company A	Engineering & Construction / Power Generation / Real Estate / Trade	67+	19.645
Company B	Construction / Energy / Tourism / Energy Electrical & Mechanical Contracting / Cement/Infrastructure Investments / Food & Beverage / Technology / Aviation	48+	46.779
Company C	Contractor and investor in construction	30+	28.990
Company D	Engineering and Contracting Group / Agricultural Production / Service Group / Investment Group	66+	11.950
Company E	Contracting / Rail System / Pipe Production / Post Tensioning / Prefabrication / Real Estate Development / Restoration / Education / Research and Development / Monitoring, Control and Communication	58+	13.849

The study includes the analysis of the selected companies' fulfillment and implementation levels of the requirements of the "Profile Descriptions" and "Approaches to Management Approach" in the guidelines. Firstly, the corporate governance and sustainability variables and materiality matrices of the companies included in the reports and the practices realized on the subject were analyzed.

Results

In this study, the sustainability reports published between 2018-2022 by Turkish construction companies ranked in the top 100 in the ENR250 list were analyzed. In the ENR 250 list, there are 40 Turkish Production companies in the top 100 in 2022. The reports used in the study belong to 5 companies on this list. Due to the differences in the sustainability policies of the companies and the voluntary publication of the reports, it has been observed that very few companies have published sustainability reports in this list, which is ranked according to their annual revenue (Table 4).

Among the companies, Company B is the organization that started sustainability reporting the earliest 2013 and has been publishing sustainability reports with a 2-year period since 2014. Company A is the company that publishes the most sustainability reports after Company B and has been publishing annual reports since 2017. Company E published a report only in 2022. In addition, only Company A has subjected its report to independent external audit.

Table 4. Annual distribution of sustainability reports published by companies.

	2018	2019	2020	2021	2022
Company A	x	x	x	x	x
Company B	x	x	x	x	x
Company C			x	x	x
Company D	x	x	x	x	x
Company E					x

All 5 companies stated that they prepared their reports in accordance with the Sustainability Development Goals (SDGs) published by the United Nation Global Compact (UNGC) (Table 5). Another joint point is that the companies prepared their reports according to the GRI guidelines. The reporting frameworks and guidelines used by the companies in order to be compliant are given in the table below.

Table 5. Frameworks and guidelines used for accordance.

	SPK*	IFC-ESG*	GRI*	SCM*	UNGC*	WBCSD*	WEPs*	WCGI*
Company A			x		x	x		x
Company B			x	x	x		x	
Company C		x	x		x		x	
Company D	x		x		x			
Company E			x		x			

***** BIST 100 (Borsa İstanbul Sustainability Index), DJSI (Dow Jones Sustainability Indexes), GRI (Global Report Initiative), SCM (Stakeholder Capitalism Metrics), UNGC (United Nation Global Compact), WBCSD (World Business Council for Sustainable Development), WEPs (Women Empowerment Principles), WCGI (World Corporate Governance Index), IFC- ESG (International Finance Corporation / Environmental - Social - Governance), SPK- ÇYS (Free market board / Sustainability compliance principles framework- Environmental governance system).

For this reason, all of the examined companies include the priority analysis in the report. Table 6 compares the topics that companies associate with sustainable development goals and their priority analyses. In the priority analysis, companies determine their sustainability approaches and include in their reports by comparing their own priorities with stakeholder priorities through the questionnaire they apply to their stakeholders within the context of stakeholder communication (Table 6).

On the other hand, it is observed that only Company B conducted a double materiality analysis. Double materiality analysis is one of the elements included in the Corporate Sustainable Reporting Directive published by the UN Commission. It is a method that reveals the impact power of the results of internal/external stakeholder prioritization on environmental and social impacts and thus on financial sustainability.

Table 6. Priority analysis – themes and companies' priority.

	Company A	Company B	Company C	Company D	Company E
HIGH	Occupational Health and Safety	Combating Climate Change	Occupational Health and Safety	Occupational Health and Safety	Occupational Health and Labour Safety
	Employee Rights and Employee Satisfaction	Emission Management	Ethics and Compliance Studies	Research /Development and Innovation	Business Ethics, Anti-Corruption and
	Economic Performance	Water Management	Diversity, Equal Opportunity and Non-Discrimination	Business Ethics and Human Rights	Employee Satisfaction
	Product and Service Quality	Occupational Health and Labour Safety	Employee Rights and Employee Satisfaction	Profitable Economic Growth	R&D and Innovation
	Customer Satisfaction	Diversity Inclusiveness, Equality	Biodiversity and Habitat Management	Talent Management and Employee Engagement	Data Confidentiality
	Combating Climate Change and Emission Reduction	Product Health, Safety and Quality	Social Impact and Responsibility	Digitalisation	Sustainable Environmental Management
	Ethics and Compliance Studies	Corporate Governance		Operational Excellence and Customer Loyalty	Corporate Governance
	Risk Management	Research /Development and Innovation		Contribution to Local Economy and Employment	Talent Management and Employee Development
	Management of Social and Environmental Impacts			Climate Crisis	Digital Transformation
	Energy Efficiency and Renewable Energy			Risk Management	Responsible Purchasing and Supply Chain
				Corporate Governance	
	Company A	**Company B**	**Company C**	**Company D**	**Company E**
MEDIUM	Diversity, Equal Opportunity and Non-Discrimination	Energy Efficiency	Energy and Emission Management	Community Investment Programmes	Combating the Climate Crisis
	Environmentally Friendly Materials, Equipment and Buildings	Waste Management	Water Management and Waste Management	Circular Economy	Customer Experience
	Employee Training and Development	Protection of Life in Water	Talent Management and Training	Multi-Stakeholder Initiatives and Collaborations	Diversity, Inclusion, Equal Opportunity
	Water Management	Sustainable Resource Utilisation			Biodiversity and Land Use
	Innovation and R&D Studies	Biodiversity Conservation			Sustainable Cities and
	Waste Management	Working Standards			Stakeholder Management and Partnerships
	Contribution to Local Economy	Employee Health and Satisfaction			Corporate Social Responsibility
	Social Investment	Emergency Management			Contribution to Local Economy and Employment
	Biodiversity and Habitat Management	Ethics and Compliance			
	Supplier Diversity and Local Procurement	Compliance with international Standards			
	Information Security & Cyber Security	Risk and Opportunity Management			
	Environmental and Social Compliance of Suppliers	Supply Management and Sustainability			
	Our Business and Our Principles Our People and Society Our Planet	Customer Satisfaction			

As another common point, the companies associated the topics that emerged as a result of the priority analysis with the 17 sustainable development goals defined by the United Nations. Sustainable development goals are; "*no poverty, zero hunger, good health and well-being, quality education, gender quality, clean water and sanitation, affordable clean energy, decent work and economic growth, industry innovation and infrastructure, reduced inequalities, sustainable and communities, responsible consumption and production, climate life below water, life on land, peace, justice and strong institutions, partnerships for the goals*" are intended to be achieved by the United Nations member countries by the end of 2030.

On the other hand, in the literature, being traded in sustainability indices and attracting investors are pointed out as the motivation for firms to publish sustainability reports. However, in the analyzed reports, only one of the companies (Company A) is included in the global indices, 3 companies are included in the regional sustainability index BIST100, while there is no information in the report that 2 companies are included in any sustainability index (Table 7).

Table 7. Indexes companies listed.

	BIST100	DJSI	FTSE4GOOD
Company A	x	x	x
Company B	x		
Company C			
Company D	x		
Company E			

As a result, it has been observed that sustainability reports are a part of companies' communication with stakeholders and the public and that they use reports as a tool. Profile descriptions and performance indicators, strategic targets and risks are commonly included in the reports. It is seen that this is due to the use of the GRI Guidelines, which are also recognized at the global level. The compliance of the companies with the GRI guidelines in the reports partly enables the comparison of the reports of the companies. However, construction companies also include different indices and frameworks in their reports in order to show their performance and compliance with corporate sustainability. In this respect, there is no unity of discourse in the reports. This creates differences in reporting content, making it difficult to compare. It is thought that this difficulty stems from the lack of any legal obligation regarding reporting and the lack of a standard regarding the reporting framework. Developing common and holistic reporting standards for construction companies will be an important tool for the future of the sector.

References

Afzal, F., Lim, B., & Prasad, D. (2017). An investigation of corporate approaches to sustainability in the construction industry. *Procedia Engineering*, *180*, 202-210.

Afzal, F., & Lim, B. (2022). Organizational factors influencing the sustainability performance of construction organizations. *Sustainability*, *14*(16), 10449.

Aksu, S. G. (2016). *Kurumsal sürdürülebilirlik ölçümü: Türkiye, Avrupa ve ABD şirketlerinde karşılaştırmalı analitik bir inceleme* [Master thesis]. Dokuz Eylül University.

Aktaş, R., Kayalidere, K., & Karğin, M. (2013). Corporate sustainability reporting and analysis of sustainability reports in Turkey. *International Journal of Economics and Finance*, *5*(3), 113-125.

Baumgartner, R. J., & Ebner, D. (2010). Corporate sustainability strategies: sustainability profiles and maturity levels. *Sustainable Development*, *18*(2), 76-89.

Borsa İstanbul (2020). *Borsa İstanbul sürdürülebilirlik endeksi*. https://www.borsaistanbul.com/files/Surdurulebilirlik_Rehberi_2020.pdf

Brundtland, G. H. (1987). *Report of the World Commission on Environment and Development: our common future*. United Nations General Assemble.

Bülbüloğlu, G. (2018), *Kurumsal sürdürülebilirlik ölçümünde dengeli performans karnesi yaklaşımı ve bir model önerisi: TOPSIS yöntemi ile şirketlerin değerlendirilmesi* [Master thesis].

Cortés, D., Traxler, A. A., & Greiling, D. (2023). Sustainability reporting in the construction industry–status quo and directions of future research. *Heliyon*.

Dow Jones Sustainability Indexes (2012). *Dow Jones Sustainability World Indexes Guide Book* (Version 11.6).

Gladwin, T. N., Kennelly, J. J., & Krause, T. S. (1995). Shifting paradigms for sustainable development: implications for management theory and research. *Academy of Management Review*, *20*(4), 874-907.

Glass, J. (2012). The state of sustainability reporting in the construction sector. *Smart and Sustainable Built Environment*, *1*(1), 87-104.

Zuo, J., Zillante, G., Wilson, L., Davidson, C., & Pullen, S. (2012). Sustainability policy of construction contractors: a review. *Renewable and Sustainable Energy Reviews, 16,* 3910-3916.

Kılıç, M., & Kuzey, C. (2017). Factors influencing sustainability reporting: evidence from Turkey. *SSRN,* 3098812.

Kocamiş, T. U., & Yildirim, G. (2016). Sustainability reporting in Turkey: analysis of companies in the BIST sustainability index. *European Journal of Economics and Business Studies*, *2*(3), 41-51.

Laskar, N., & Maji, S. G. (2016). Corporate sustainability reporting practices in India: myth or reality? *Social Responsibility Journal*, *12*(4), 625-641.

Ludwig, P., & Sassen, R. (2022). Which internal corporate governance mechanisms drive corporate sustainability? *Journal of Environmental Management*, *301*, 113780.

Luo, J., & Liu, Q. (2020). Corporate social responsibility disclosure in China: do managerial professional connections and social attention matter? *Emerging Markets Review*, *43*, 100679.

Perez-Batres, L. A., Miller, V. V., & Pisani, M. J. (2011). Institutionalizing sustainability: an empirical study of corporate registration and commitment to the United Nations global compact guidelines. *Journal of Cleaner Production*, *19*(8), 843-851.

Şahin, Z., Çankaya, F., & Karakaya, A. (2018). Sürdürülebilirlik raporlarinin sektörlere ve yillara göre analizi. *Uluslararası İktisadi ve İdari İncelemeler Dergisi*, *20*, 17-32.

Türker, E. (2021). *İnşaat firmalarında sürdürülebilirlik stratejilerinin; firma rekabet gücüne ve firma sürdürülebilirlik performansına etkisinin araştırılması* [Master thesis]. Balıkesir University.

Zhang, Q., Oo, B. L., & Lim, B. T. H. (2022). Corporate social responsibility practices by leading construction firms in China: a case study. *International Journal of Construction Management*, *22*(8), 1420-1431.

Zuo, J., Wilson, L., Zillante, G., Pullen, S., & Chileshe, N. (2013). Appraising corporate sustainability of construction contractors: concepts and approaches. *Sustainable Business*, 233-247.

Factors Affecting the Cost Analysis of Rooftop Solar Energy Constructive Systems and Connection Elements

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Abstract

Renewable energy is becoming increasingly important as energy prices rise and depletable resources decrease. As a renewable energy source, solar energy systems have a variety of uses. In Turkey, the use of rooftop solar energy systems is often preferred in large cities where land costs, energy production and consumption are high. To enable buildings to use solar energy, various fasteners and structural systems are used when installing solar systems on rooftops. However, the selection of materials used in rooftop solar energy systems should be changed according to environmental and mechanical conditions. Along with these variable conditions, the constructive system cost, fastener costs, and project costs will also change. Therefore, variables that affect the system must be identified with priority as part of the cost analysis during the feasibility process in order to prevent possible problems that might arise during the project implementation phase. In this context, the aim of this study is to determine the factors affecting the cost analysis of constructive and connection elements of rooftop solar energy systems. The findings of this study provide important information to help EPC companies analyze their investments in rooftop solar energy systems.

Keywords: *construction, constructive systems, cost analysis, feasibility, solar energy.*

Introduction

It is necessary to carry out interdisciplinary research to carry out the project process of solar energy systems efficiently and accurately (Sharif et. al, 2013). In Turkey, energy and electrical engineers are involved in installing solar panels on rooftops along with civil engineers. The engineer creates a list of materials to be used in the project and static project according to the electrical design of the electrical and power system. For static project planning according to design, the regulations of TS-EN-1991 and TS-498 are used. These regulations are used to determine the loads on the roof. Static projects also need to be designed according to the existing structure and the planned photovoltaic system. The requirements identified during the design phase determine the cost of the project. In this type of project where installation cost is high and maintenance cost is low, installation cost and analysis are very important for project applicability. The annual increase in electricity consumption in Turkey and the dependence on foreign energy sources have increased the importance of clean energy technology. Reducing initial installation costs will be the most important factor for widespread use of solar and wind power, which are clean energy technologies (Güven, 2016). For this reason, it is important to accurately select the area where the project will be carried out by conducting an accurate pre-project cost analysis.

Depending on the arrangement of the modules, the load of the photovoltaic system is determined according to different design principles. A solar system mounted diagonally on the roof is considered as an open canopy. A solar system installed parallel to the roof is considered as a roof-covering element and is calculated from the roof load. In this case, the conditions affecting the system are also different. The structural elements of a rooftop solar power system vary depending on the roof on which it is installed. In addition to environmental factors, footprint is also known to influence cost. In this context, this study’s purpose is to support the project feasibility process and cost analysis by investigating the factors that influence the construction costs of solar energy systems and the conditions that indirectly influence them.

Construction Systems and Elements of a Solar Energy System on the Roof

The construction system for rooftop solar power generation systems is a construction system that aims to more efficiently operate and stabilize solar panels, which are an important element of energy systems. Since it occurs in open areas, aluminum materials are more preferred as they oxidize less than steel. One reason why aluminum is preferred is that it has a lower density than steel, which places less stress on the structure. Rooftop solar power generation systems have different building systems. The type of building system used in this study is one of the most used systems in Turkey. Starting from the connected roof, the system parts can be listed as follows:

- **Roof Mounting:** These are the elements used to mount a rooftop solar system to the roof. It depends on the type of roof.
- **Aluminum profile:** Element that creates a connection between the roof fixing and the clamp and triangular leg.
- **Clamps and triangular legs:** These are the elements that connect the solar modules to the building system. Triangular legs are only used in angled systems.
- **Bolts and Fasteners:** Being a modular system, bolts and fasteners are used to connect many major elements.

Types of Rooftop Solar Energy Systems

There are three different types of systems investigated in this study; such as tilted solar energy systems (single-sided inclined systems and double-sided inclined systems), and parallel solar energy systems, respectively. One-sided and double-sided angled systems are used on flat roofs to better capture the sun's angle. Because there is a gap between the installed system and the structure, installed rooftop solar panels act like a porch. A PV system parallel to the roof has a small gap between it and the building, but this is not considered a gap in the sense of the TS-EN-1991-1-4 regulation, so static calculations are performed as a roof.


Figure 1: Tilted solar energy systems (left), parallel solar energy systems (right).

In this study, domestic and small-scale solar power plant projects are excluded because their main purpose is not to earn revenue from power generation and sales. To exclude this application field, the DC value of the compared system was determined to be 1 MW. In this case, the rooftops on which a solar power plant of this scale can be installed would be buildings such as industrial buildings or shared-use schools or hospitals. Examining the roofs of these buildings reveals different types of roofs. These coatings are mainly: Trapezoidal sheet metal roofs can be classified as standing seam roofs, membrane roofs, and concrete roofs. These types of roofs are tested differently for conditions.

Factors Influencing the Construction Cost of Rooftop Solar Energy Systems

The building industry is transitioning to sustainability, with solar panel integration leading the way (Vijayan et. al, 2013). The construction system of a rooftop solar power system is a structural system. As with all structural systems, costs vary based on design requirements and loads. Different structures have different design requirements, and different solar systems require different roofs. Therefore, details related to factors influencing the load of different types of systems investigated in this study are presented in details below.

Factors Influencing the Load of Double-Sided Inclined and Single-Sided Inclined Rooftop Solar Energy Systems

Sloped roof photovoltaic systems are considered rooftop veranda structures, so the operating conditions are similar. The only difference between them is that one resolves as a unidirectional angled stem, whereas a bidirectional angled stem conforms to its own shape and resolves as a regulation-compliant stem. Wind loads are calculated using the EN-1991-1-4 standard. The main conditions that affect load calculations according to regulations are:

- **Land category:** There are land categories designated in the regulations numbered 0-1-2-3-4. According to these land categories, wind loads are highest in land zone 0 and lowest in land zone 4.
- **Basic Wind Speed:** Basic wind speed is determined according to TS-498. It varies between 28 and 46 m/s. Increasing the simple wind speed increases the load on the panel (TS EN 1991-1-4:2005).

- **Height of Shed:** As the height of the building system used changes, the wind loads will also change. As the canopy height increases, so does the wind load (TS EN 1991-1-4:2005).
- **Shed angle:** For calculations according to standard EN-1991-1-4, the stem angle has a direct effect on the wind load. As the angle increases, the wind load increases (TS EN 1991-1-4:2005).
- **Wind Loads:** As wind loads increase, the cross-sectional area increases or fastening frequency increases to increase the stiffness of the building system. (ÇYTHYE:2019) This situation directly affects construction costs. Since the porch height is below the minimum height required by ordinance, there is no change to the project-based calculation. In addition, other substances also directly affect wind loads. Simple wind speed is determined by the height of his TS-498 in Türkiye. In this case, the height of the roof where the solar roof system is installed has an indirect effect on the wind loads. The parapet of the roof on which the solar energy system is installed creates obstructions around the system and therefore indirectly affects the wind loads by affecting the real estate value of the roof on which these panels are installed also affect the slope of the panels above it, and therefore indirectly affects the wind load.

Factors Influencing the Load of Parallel Rooftop Solar Energy Systems

Since the roof-parallel PV system is considered a roof cover, the wind loads are calculated according to the EN-1991-1-4 standard. The main conditions that affect regulatory load calculations are:

- **Land category:** There are land categories designated in the regulations numbered 0-1-2-3-4. According to these land categories, wind loads are highest in land zone 0 and lowest in land zone 4(TS EN 1991-1-4:2005).
- **Simple wind speed:** Since the PV system parallel to the roof is calculated as a roof, the wind speed is assumed to be 28 m/s according to TS-498. Since the building starts from the lowest ground, the height of the simple wind speed also starts from zero level. Increasing the simple wind speed increases the load on the panel (TS EN 1991-1-4:2005).
- **Building height:** When calculated according to regulation EN-1991-1-4, the building height has a direct effect on the wind load. Wind loads increase with increasing altitude (TS EN 1991-1-4:2005).
- **Roof angle:** Roof angle determines the shape of the roof and its effect depends on the shape of the roof. A roof that is considered a flat roof from 0 degrees to 5 degrees is a pitched roof if it slopes more than 5 degrees. As the angle increases, the wind load normal to the roof surface decreases, but the change in angle increases the force acting in the z direction (TS EN 1991-1-4:2005).
- **Roof shape:** Depending on the roof shape, the solution system specified in the regulations is used. Different wind loads are determined depending on the type of roof, such as an enclosed roof or a flat roof (TS EN 1991-1-4:2005).
- **Parapet height:** Directly affects wind loads. Increasing the height of the parapet reduces wind loads (TS EN 1991-1-4:2005).
- **Wind Loads:** As wind loads increase, the cross-sectional area increases or fastening frequency increases to increase the stiffness of the building system. This situation directly affects construction costs. Roof-parallel photovoltaic systems eliminate parapet effects depending on the slope of the roof. Parapets only reduce wind loads on flat roofs (roofs with a pitch angle of less than 5 degrees). In Turkey, unless there

is a simple wind speed measurement, 28 km/h is used by regulations. The reason it does not change with building height is because we use simple wind speed as the starting height of the target building.

Cost-Effectiveness of Roofing Material Types in Rooftop Solar Energy Systems

Proper fasteners are required to properly connect the roof solar system to the roof. These fasteners vary depending on the type of roof and vary in price and strength. These elements are:

- Lateral connection member to trapezoidal roof slope
- Top connection member to trapezoidal roof pitch
- Trapezoidal short roof profile made of aluminum
- Standing seam roof connection member
- Membrane roof connection member
- Concrete roof connection member
- Ballast system construction system.

Trapezoidal coatings require purlin fasteners, but their strength is not sufficient as roof fasteners for installing rooftop solar energy systems. However, the cost and strength of purlin fasteners vary depending on the type of roof.

Effects of Snow on Rooftop Solar Energy Systems

The EN-1991-1-3 standard is used when calculating snow loads. Snow loads directly affect building system loads. According to the regulations, the following criteria apply when calculating snow loads.

- Snow area
- Roof type
- Planned life of the structure.

Snow loads directly affect the loading of the building system, so increasing it will increase the system cost. For this reason, snow loads are one of the most important conditions to evaluate during the feasibility process. In areas outside of zones with high wind loads, snow loads determine the design loads.

Results

The conditions that influence the structural cost of rooftop solar PV systems are the structural loads specified by regulations and their combinations. These loads are wind loads and snow loads. Indirect conditions that determine design loads also affect the cost of the structural system. These indirect conditions are wind speed, structure height, etc., and were determined as. There are various fasteners used to connect to the roof. Replacing fasteners also changes the cost of the construction system.

Rooftop solar PV systems are installed on existing buildings and therefore need to work in harmony with the existing building. For this reason, it is necessary to prioritize materials and construction systems that are compatible with the structure. Before making an investment decision, the influence of existing structures, environmental conditions, and the type of solar energy system must be considered in the feasibility process.

When assessing environmental conditions, it is necessary to assess not only the energy production but also the building installation conditions. These evaluations must consider many factors such as wind loads, snow loads, roof geometry, and roof covering. Conditions such as wind speed, terrain category, parapet dimensions, and snow cover also indirectly influence these factors and change the design context. For this reason, it is important to pay attention to the details of the feasibility process to identify the requirements of the design conditions and ensure their control.

References

European Committee for Standardization (2005). *EN 1991-1-4:2005. Eurocode 1: Actions on Structures - Part 1-4: General Actions - Wind Actions*.

European Committee for Standardization (2015). *EN 1991-1-3:2003+A1:2015 Eurocode 1: Actions on Structures - Part 1-3: General Actions - Snow Loads*.

Güven, A. F. (2016). Afyon Oruçoğlu Terma Otelinin enerji ihtiyacini karşilayacak güneş enerji sisteminin tasarlanmasi, optimizasyonu ve maliyet analizi. *Uluslararası Sosyal Bilimler ve Eğitimde Stratejik Araştırma Konferansı*, pp. 1-18.

Sharif, S., Gentry, T. R., Yen, J., & Goodman, J. N. (2013). Transformative solar panels: a multidisciplinary approach. *International Journal of Architectural Computing*, *11*(2), 227-245.

Turkish Civil Engineer Chamber (2019). *Principles related to the design, calculation and construction of steel structures*. TMMOB Department of Civil Engineers.

Turkish Standards Institute (2002). *TS 498: loads and forces used in the design of construction components*.

Vijayan, D. S., Koda, E., Sivasuriyan, A., Winkler, J., Devarajan, P., Kumar, R. S., & Vaverková, M. D. (2023). Advancements in solar panel technology in civil engineering for revolutionizing renewable energy solutions—a review. *Energies*, *16*(18), 6579.

Potentials of Circular Economy Principles in Building Life Cycle

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Abstract

Circular economy (CE) is a design concept which aims to use resources in a more renewable way to extend the value and life of all kinds of products including the built environment. Achieving a circular economy will be reached through holistic circular thinking and sustainable practice approach on all kind of industries, including Architecture-Engineering-Construction-Operation (AECO) industry. In this study, from design to construction and operation, the current situation and future potentials of the circular economy in the building life cycle is examined. Circular economy strategies are categorized according to 10Rs. This study aims to evaluate the potentials of circularity in project management in order to show how 10Rs of circularity can be used in various phase of building life cycle. Building life cycle is analyzed according to BS EN 15978:2011 schematic phases. 10Rs of circularity are examined throughout the life cycles: production (A1-A3), construction (A4-A5), use (B1-B5), end of life (C1-C4) and beyond the life cycle (D). By employing a through literature review, it is also targeted to provide the applicability areas of circular economy principles in building life cycle. Within the scope of the study, existing literature of Circular Economy and Building Life Cycles is examined between 2010 and 2023. Bibliometric analysis is conducted through Scopus and Web of Science (WoS). Articles and conference papers at the intersection of the research area are investigated. Scientific studies are evaluated according to their publication dates, published sources and citation numbers, keywords and published resources. Results of the analysis are visualized with the VOSviewer application. Furthermore, building life cycle stages are analyzed accordingly 10Rs.

Keywords: *circular economy, circularity, building life cycle, bibliometric analysis.*

Introduction

Circular economy (CE) is a design concept which aims to use resources in a more renewable way to extend the life of all kinds of products including buildings. Switching from "take-make-dispose" based linear economy to “make-use-reuse-recycle” based circular economy model will reduce the impact of climate change. Achieving a circular economy will be reached through holistic circular thinking and sustainable practice approach on all industries, including AECO industry since it is responsible of 40% of carbon dioxide emissions and one third of total waste (IEA, 2019). In this regard, AECO has to redefine and re-evaluate its process and techniques within the circular transformation. The CE model provides a great opportunity for the reduction of primary material usage, thereby protecting material resources and reducing the carbon foot print (EMF, 2013). There are many different definitions of CE and circularity in the literature. Kirchherr et al. (2017) examined 114 different definitions of circular economy, then extended this work (Kirchherr et al., 2023) to 221 definitions of CE; the terms "reduce", "reuse" and "recycle" and their various combinations are common points of all definitions including "regenerative". UN Environmental Program (UNEP, 2020), Potting et al. (2017) and Kirchherr et al. (2017) have defined circular economy strategies with 10Rs: Refuse (R0), Rethink (R1), Reduce (R2), Reuse (R3), Repair (R4), Refurbish (R5), Remanufacture (R6), Repurpose (R7), Recycle (R8) and Recovery (R9). In this regard, within the framework of this study, these 10Rs are accepted as CE strategies. This study aims to evaluate the potentials of circularity in project management in order to show how 10Rs of CE can be used in various phase of building life cycle. The objectives are (1) point out the current situation through bibliometric analysis and (2) create a relation between project management specialized areas and R strategies.

Building Life Cycle

CE can further be described as a living economic system, with value creation based on use and re-use instead of waste & demolition-based system. CE starts with the beginning of a building's life, so pre-design, design and construction phases of a building play an important role for minimizations of resources use and waste generation. In order to maximize the potential for reuse and value of building and its components, the "Alternative Building Life Scenarios" and "End-of-Life" concept play crucial roles in the building life cycle. EU defined schematic phases of the life cycle of a building or construction product as BS EN 15978:2011 (2011) (Figure 1). The life cycle schema was composed of 5 stages and 15 modules. Also, approximate carbon emissions (CO_2 emissions) for the stages were integrated to the schema.

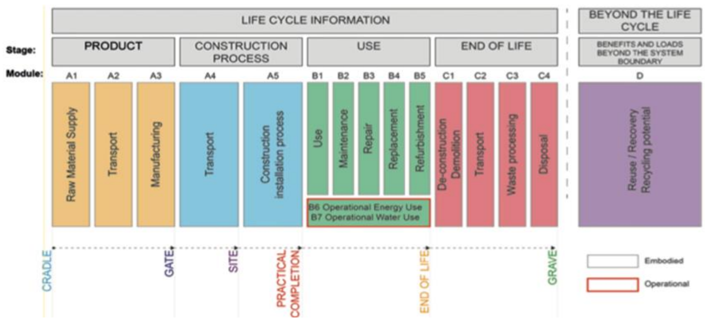


Figure 1: Life cycle, stages and modules.

Product & Construction Stage is characterized by the A, covering 5 modules. The modules A1–A3 are product phase which is also known as 'cradle to gate' and, are carbon emissions released during raw material extraction, processing, manufacture and transportation of materials between these processes until the product leaves the factory gates to be taken to site. A4-A5 (Construction process stage) are associated with the embodied carbon released during the transport of materials/products to the site (A4), the energy usage due to activities on site (machinery use, etc.), and the carbon emissions associated with the production, transportation, and end of life processing of materials wasted on-site. Use Stage is symbolized by the B and have 5 modules. Use Stage (B1-B5) includes the carbon emissions released due to use, maintenance, repair, replacement, refurbishment, and operational energy. These actions are also part of CE strategies. Module B4 (replacement) is often the focus of the use stage when embodied carbon is being considered (Gibbons & Orr, 2020) The embodied energy (EE) and embodied carbon (EC) are calculated over the whole life of the building ('cradle to grave'), following the methodology and boundary conditions set out in the recently published CEN TC 350 standards on Sustainability of Construction Works (BSI, 2012). Use stage can also be named as Operation stage and it is related to Facility management. The End-of-Life Stage of a building is characterized by the C, end-of-life stage. The latter refers to the energy used and the environmental impact, in terms of greenhouse gas (GHG) emissions, generated by all activities of demolition, deconstruction, dismantling of a building or construction product (C1, Deconstruction–demolition), the transport of demolition waste from the construction site to an appropriate storage or disposal site (C2, Transport), the sorting, collection and treatment of demolition waste (C3, Waste processing) and the disposal of demolition waste at an appropriate disposal site (C4, Disposal). Stage D named as "beyond the life-cycle" in 2011. In this study, from design to construction, operation and end-of-life stages, the current situation and future potentials of the circular economy in the building life cycle is examined. This study aims to evaluate the potentials of circularity in project management in order to show how 10Rs of circularity can be used in various phase of building life cycle. Building life cycle is analyzed according to BS EN 15978:2011 schematic phases. 10Rs of circularity are examined throughout the life cycles: production (A1-A3), construction (A4-A5), use (B1-B5), end of life (C1-C4) and beyond the life cycle (D).

Methodology

This study aims to evaluate the potentials of circularity in project management in order to show how 10Rs of circularity can be used in various phase of building life cycle. The methodology in this study involves two phases (Figure 2). In the first step, relations between circularity and building life cycle were examined through bibliometric analysis, Scopus and VosViewer. Major concepts and related topics were revealed through these analyses. In the second step, building lifecycle stages were categorized according to the 10Rs applicability areas: R0-R2 are related to Production (A1-A3), Construction (A4-A5), R3-R7 are related to Use phase (B1-B5), R8-R9 are related to End of Life (C1-C4) and Beyond the Life Cycle (D).

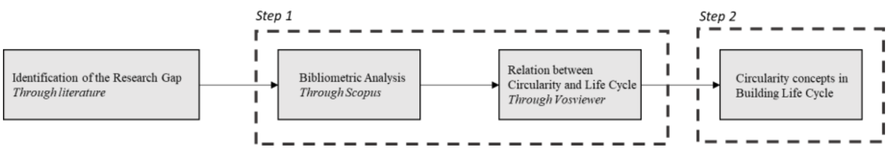


Figure 2: Methodological flow of the study.

By employing a through literature review, it is also targeted to provide the potentials of circular economy principles in building life cycle. Within the scope of the study, existing literature of Circular Economy and Building Life Cycle is examined for ten-years period time between 2013 and 2023. Bibliometric analysis is conducted through Scopus and Web of Science (WoS). Articles, books, book chapters and conference papers at the intersection of the research area are investigated. Scientific studies are evaluated according to their publication dates, published sources and citation numbers, keywords and published resources. Results of the analysis are visualized with the VOSviewer application. The first step of this study's methodology is based on bibliometric analysis to understand and reveal the current relations between circular economy and building life cycle. The literature sample was retrieved from Scopus and Web of Science (WoS) databases. Scopus and Web of Science are accepted as the world's largest peer-review databases. Besides, keywords which had same meaning were organized using the TITLE-ABS-KEY as follows: ("lifecycle" OR "life cycle") and ("lifecycle assessment" OR "LCA") and ("end of life" OR "EoL"). Accordingly, the first retrieval resulted in identification of 923 publications, 647 from Scopus and 276 from WoS. The time span for review was from January 2010 to December 2023. Identification phase included removal of duplicated publications; 202 publications were excluded in this phase. Screening phase included removal of same publications and filtering process according to certain criteria. Only articles in English language and with full text available were considered in this study. Also, only engineering, and multidisciplinary areas were included; other subject areas were excluded. Additionally, notes, text notes, editorial notes were removed. 114 papers were not retrieved because of lack focus on building life cycle. The number of publications assessed for eligibility was 467 and these continued to the PRISMA protocol. Inclusion phase provided additional criteria on aims and relations to the related topic were analyzed in detail.

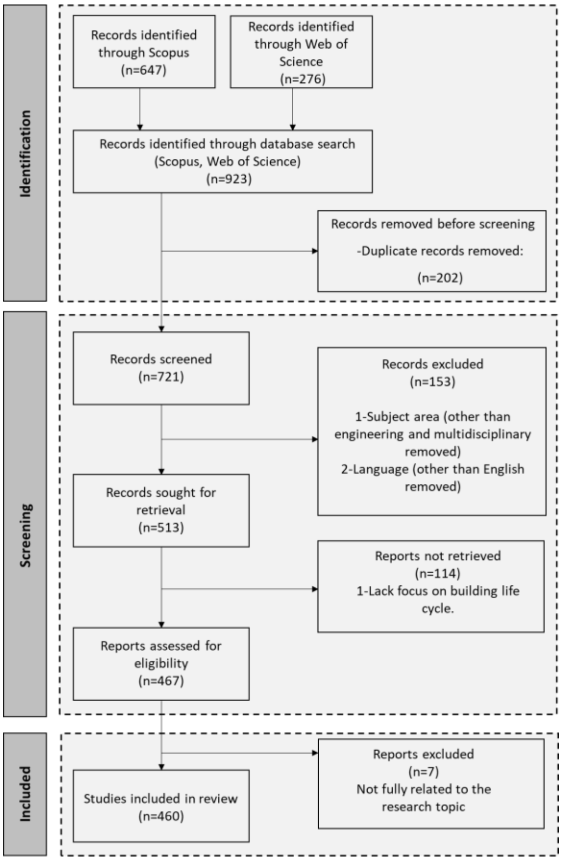


Figure 3: Building life cycle, stages and modules.

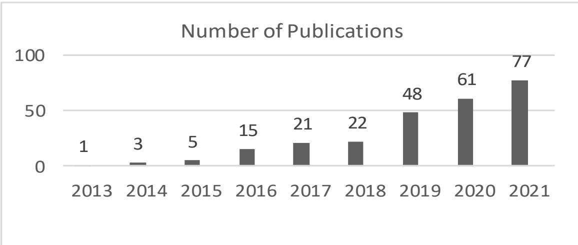
In this phase, 7 paper was removed. At the end of the PRISMA protocol, 460 papers remained.

Bibliometric Analysis

The methodology of analyses was based on bibliometric analysis in order to understand and reveal the current relations between circularity concepts and building life cycle. In general, bibliometric analysis was applied to map the scientific retrieved data for evaluation of themes, dynamic aspects of data, and processing a wide range of information (Khan et al., 2021). This study utilized bibliometric analyses conducted with VOSviewer software.

Number of Publications According to Year

Figure 4 illustrates the publications classified according to years. It is seen that the number of publications increased throughout the years. There are two thresholds, as 2016 and 2019. From 2015 to 2016, number of publications are tripled and from 2018 to 2019 the publications number have increased more than double.



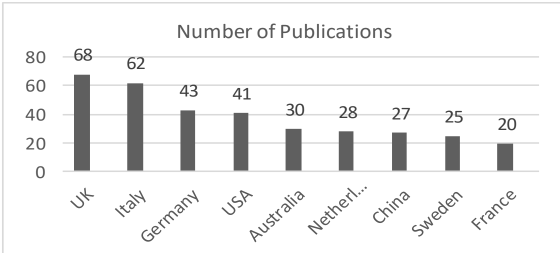


Figure 4-5: Publications by year & countries.

Number of Publications According to Country

Figure 5 illustrates the publications by the 9 countries. The wide distribution of diversity across different geographic areas indicates a worldwide commitment to transforming the built environment in a circular and sustainable way. Articles from the UK (68), and Italy (62) are at the forefront of this new field, which account for 28 % of all publications. Next comes Germany with 43 publications and USA, with 41 publications, and these are followed by Australia (30), Netherlands (28), China (27), Sweden (25) and France (20). In total, 69 different countries published papers on this topic but only 33 of them have more and equal than 5 papers: India (19), Canada (15), Denmark (13), Japan (13), Finland (12), Norway (12), Brazil (11), Hong Kong (11), Austria (10), Greece (10), Spain (10) and Malaysia (10).

Author-based Analysis

This analysis aims to point out the most significant academic achievements on CE in built environment research (Table 1). For the impacts, Sassanelli, C. received the highest citations with 7 documents and had the largest number of citations. In addition, Terzi, S. and Rosa, P. have high impact in this field with 533 and 499 citations. Furthermore, Charef, R. and Turner, C. have 6 and 5 documents respectively.

Table 1. Authors citation analysis.

Author	Number of Documents	Citations
Sassanelli, C.	7	535
Charef, R.	6	160
Terzi, S.	6	533
Turner, C.	6	110
Rosa, P.	5	499
Oyekan, J.	5	79
Germani, M.	5	55
Iyer-Raniga, U.	5	53
Mesa, J.A.	5	47

More details of highly cited articles were shown in Table 2. The most cited article focused on future of blockchain technology for circular supply chain management. Second and fourth most cited articles are reviews. Third article discussed closed-loop material flow. Fourth article focused on developing a digital tool for CE. Also, it is seen that all the papers combine circularity with sustainability and digital technologies.

Table 2. Paper citation analysis.

Author	Source Title	Citations	Year
Esmaeilian, B., Sarkis, J., Lewis, K., Behdad, S.	Blockchain for the future of sustainable supply chain management in Industry 4.0	410	2020
Sassanelli, C., Rosa, P., Rocca, R., Terzi, S.	Circular Economy performance assessment methods: a systematic literature review	386	2019
Jawahir, I.S., Bradley, R.T.	Technological Elements of Circular Economy and the Principles of 6R-Based Closed-loop Material Flow in Sustainable Manufacturing	335	2016
Esmaeilian, Wan, B., Lewis, K., Duarte, F., Ratti, C. Behdad, S.	The future of waste management in smart and sustainable cities: A review and concept paper	273	2018
De los Rios, I.C., Charnley, F. J.	Skills and capabilities for a sustainable and circular economy	271	2017
Ruiz, L.A.L., Roca Ramón, X., Gasso Domingo, S.	The circular economy in the construction and demolition waste sector – A review and an integrative model approach	262	2020
Zheng, P., Wang, Z., Chen, C.H., Khoo, L.P.	A Survey of Smart Product-Service Systems: Key Aspects, Challenges and Future Perspectives	243	2019
Foster, G.	Circular economy strategies for adaptive reuse of cultural heritage buildings to reduce environmental impacts	227	2020
Henry, M., Bauwens, T., Hekkert, M.P., Kirchherr, J.	A Typology of Circular Start-Ups: An Analysis of 128 Circular Business Models	210	2020
Baduge, S. K., Thilakarathna, S., Perera, J. S., Arashpour, M., Sharafi, P., Teodosio, B., Shringi, A., & Mendis, P.	Artificial intelligence and smart vision for building and construction 4.0: machine and deep learning methods and applications	200	2022
Nußholz, J.L.K.	A circular business model mapping tool for creating value from prolonged product lifetime and closed material loops	150	2018
Ayeleru, O.O., Dlova, S., Akinribide, O.J., Ntuli, F., Kupolati, W.K., Marina, P.F., Blencowe, A., Olubambi, P.A.	Challenges of plastic waste generation and management in sub-Saharan Africa: A review	116	2020
Akanbi, L., Oyedele, L.O., Omoteso, K., Bilal, M., Akinade, O.O., Anuoluwapo, O., Delgado, M.D., Owolabi, H.A.	Disassembly and Deconstruction Analytics System (D-DAS) for Construction in a Circular Economy	116	2019
Ranjbari, M., Saidani, M., Esfandabadi, Z.S., Peng, W., Lam, S.S., Aghbashlo, M., Quatraro, F., Tabatabaei, M.	Two decades of research on waste management in the circular economy: Insights from bibliometric, text mining, and content analyses	105	2021
Hauschild, M. Z., Kara, S, Røpke, I.	Absolute sustainability: Challenges to life cycle engineering	101	2020

Co-occurrence of Keywords Bibliometric Analysis

Figure 6 offers an overview of the data selected during the eligibility phase of the PRISMA protocol, the size of the circles represents the frequency and strength of connections. Larger circles indicate higher importance within the network.

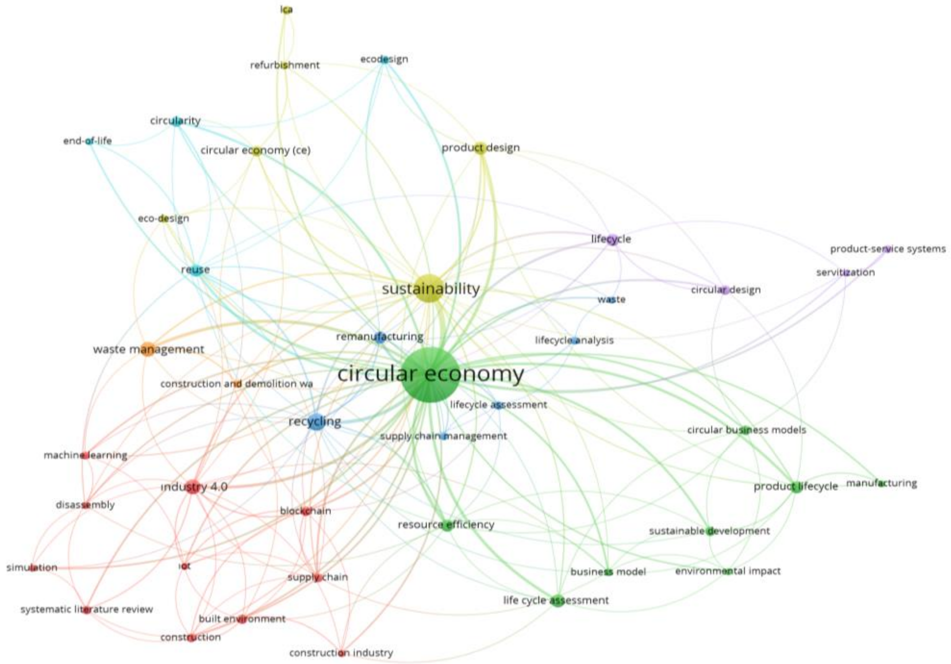


Figure 6: Co-occurrence of keywords analysis.

CE and sustainability have larger circles, indicating higher importance in the network. These two are followed by recycling, resource efficiency, remanufacturing, reuse, waste management, product design, industry 4.0, supply-chain management and lifecycle assessment. "CE" is the most connected keyword in built environment research with 291 occurrences, followed by "sustainability" with 75 occurrences and "lifecycle assessment" with 49 occurrences. “Recycling”, “waste management” and “industry 4.0” have large occurrences. Other significant keywords are resource efficiency, reuse, remanufacturing, product design, circular design and sustainable development. The total link strengths & occurrences are shown in Table 3.

Table 3. Co-occurrence of keywords analysis.

Keyword	Occurrences	Total Link Strength
Circular economy	291	342
Sustainability	75	119
Life cycle assessment	49	70
Recycling	27	47
Waste management	20	28
Industry 4.0	19	37
Resource efficiency	14	27
Reuse	13	31
Remanufacturing	13	24
Product design	15	30
Circular design	16	26
Sustainable development	9	15

Potentials of Circularity in Building Life Cycle

A key aspect of implementing the CE involves companies altering their business models through strategies known as R-strategies. In this study, 10Rs of CE is accepted as the main strategies. These are Refuse (R0), Rethink (R1), Reduce (R2), Reuse (R3), Repair (R4), Refurbish (R5), Remanufacture (R6), Repurpose (R7), Recycle (R8) and Recovery (R9).

Table 4. Potentials of R's according to the phases.

Stage	Module	Specified Area	Building Life Cycle Phase	R Strategies	Key Aspects
Production	A1-A3	Design Management	Design & Construction	R0 - Refuse	carbon-depended built environment
		Supply-Chain Management		R1 - Rethink	material, usage, ownership
Construction	A4-A5	Construction Site Management		R2 - Reduce	source: raw material, energy, water consumption
Use	B1-B5	Facility Management	Operation	R3 - Reuse	multiple usage, sharing principles, second life
				R4 - Repair	extend the life and value
				R5 - Refurbish	improvement of building elements and products
				R6 - Remanufacture	combine new elements to strengh existing
				R7 - Repurpose	alternative functions and new products
End-of-Life	C1-C4	Waste Management	End-of-Life & Return	R8 - Recycle	waste and water
Beyond the Life Cycle	D1-D2			R9 - Recover	energy recovery

According to the Table 4, R0-R2 are related to Design & Construction Phase, R3-R7 are related to Operation Phase and R8-R9 are related to End-of-Life and Return Phase. Design & Construction phase is about design, supply-chain and construction site management. It involves circular design, and circular construction techniques. Circular design strategy adopts the "take-make-use-reuse" concept to different scales from urban to material scale. CE foresees transforming architecture to become more responsive to environmental and social realities; to a shift towards sustainable and circular design thinking. Circular design covers consideration of systems as integrated, flexible, dynamic and adaptable to different life scenarios. On a building scale, circular design involves circular construction techniques and materials such as: modularity; transformability and low carbon material usage. Refusing the carbon-depended built environment. It involves refusing toxic materials, single-use, overconsumption, fossil fuel-based energy consumption. Rethinking is about considering materials, functions and alternative life scenarios and ownership. Reduce aims to decrease all kinds of source consumption such as material, water, energy, money. For the Operation phase, one way of moving towards a circular built environment is to extend the service life of buildings through various design approaches such as adaptive design, adaptive reuse, design for disassembly(DfD) and design for repair& remanufacturing (Ness & Xing, 2017; Pomponi, De Wolf, & Moncaster, 2018; Hopkinson, De Angelis, & Zils, 2020; Joensuu, Edelman & Saari, 2020; Minunno et al., 2020). Product service system (PSS) practices are discussed as relevant to the context of the built environment, as these systems could help facilitate maintenance activities and service life extensions of buildings through adaptive reuse and the more efficient use of buildings (e.g., sharing economy principles), which could decrease resource consumption and limit the growth of the building stock (Joensuu et al., 2020). Reuse is directly about the increasing the life and value of the buildings through multiple usage and sharing principles. Also, reusing the building elements and thinking the second life of these are involved. The reuse of materials or systems or buildings, in general products at end-of-life is optimised, facilitating a circular flow of products. This is enhanced with improved collection and reprocessing of materials and optimal cascading by creating value in each stage of reuse and recycling: Design for repair, Design for refurbish / remanufacture, repurposing, Design for recyclability, design for disassembly, reuse and recycling. Repair targets the extension of the life and value of the buildings and building components. Refurbish is about improvement of the building elements and products. Remanufacture strategy combines new building elements to strength the existing ones. Repurpose focuses on alternative functions to extend the usage of the building. Recycle can be downcycle or upcycle. It is about recycling the waste and water. Recover means energy recovery.

Conclusion

This study discussed the current situation of CE considering the building life cycle phases. Accordingly, the potentials of CE within the building life cycle were investigated based on a comprehensive literature review, to provide an insight for researchers and the professionals. Country-based, citation-based, author-based and keyword-based analyses conducted based on Scopus and WoS and mapping has done through VosViewer. Additionally, R strategies as CE potentials for the life cycle were explored. Reuse, remanufacture, recycle and resource efficiency were the main Rs. Resource efficiency is in relation with the Refuse, Rethink and Reduce. Second part of this study involves constructing a relation between R strategies and building life cycle phases. Building life cycle is analyzed according to BSI. 10Rs of CE are examined throughout the life cycles: Design & Construction (A1-A5), Operation (B1-B5), End-of-Life & Return (C1-D). Design & Construction includes supply-chain, design and construction site management and is directly related with Refuse, Rethink, Reduce; Operation includes facility management and is related to Reuse, Repair, Refurbish, Remanufacture and Repurpose. End-of-Life & Return is related to waste management; Recycle and Recover are the circularity strategies. Moreover, key aspects to examine in detail for implementing real-life solutions are explored considering project management specified area, building life phase and R strategies. For further studies, possible real-life CE applicability scenarios and models can be developed involving academia-industry or / and academia-industry-governance collaboration. Local project management strategies can be developed focusing on circular business models in AECO industry.

References

BSI. (2011). BS EN 15978:2011. *Sustainability of Construction Works—Assessment of Environmental Performance of Buildings*—Calculation Method; BSI: London, UK.

BSI. (2012). BS EN 15804. *Sustainability of construction works.* In Environmental product declarations. Core rules for the product category of construction products, British Standards Institution: London, UK.

EMF. (2013). *Towards the circular economy, Opportunities for the Consumer Goods Sector*.

Gibbons, O. P., & Orr, J. J. (2020). *How to Calculate Embodied Carbon*; The Institution of Structural Engineers: London, UK.

Hopkinson, P., De Angelis, R., & Zils, M. (2020). Systemic building blocks for creating and capturing value from circular economy. *Resources, Conservation and Recycling*, 155, 104672.

International Energy Agency (IEA). (2019). *2019 Global Status Report for Buildings and Construction:* Towards a zero-emissions, efficient and resilient buildings and construction sector.

Joensuu, T., Edelman, H. & Saari, A. (2020). Circular economy practices in the built environment. *Journal of Cleaner Production*, 276, 124215.

Khan, A., Sepasgozar, S., Liu, T. & Yu, R. (2021). Integration of BIM and Immersive Technologies for AEC: A Scientometric-SWOT Analysis and Critical Content Review. *Buildings*, 11, 126.

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, 127, 221–232.

Minunno, R., O'Grady, T., Morrison, G. & Gruner, R. (2020). Exploring environmental benefits of reuse and recycle practices: A circular economy case study of a modular building. *Resources Conservation and Recycling.* 160.

Ness, D. & Xing, K. (2017). Toward a Resource-Efficient Built Environment: A Literature Review and Conceptual Model. *Journal of Industrial Ecology*. 21.

Pomponi, F.; De Wolf, C. & Moncaster, A. eds. (2018). *Embodied Carbon in Buildings: Measurement, Management, and Mitigation*. Springer.

United Nations Environmental Program (UNEP). (2020). *Emissions Gap Report 2020*. https://www.unep.org/emissions-gap-report-2020 Last accessed date: 16.05.2024.

An Evaluation of Ecological Design and Construction Strategies for Enhancing the Resilience of the Built Environment

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Abstract

Resilience is a researched topic across different academic fields. In the context of the built environment resilience refers to the ability to bounce back to normalcy after impacts. Restoring the built environment post effects is a costly and resource intensive process. Solutions emerging from concerns present opportunities to strengthen the resilience of our built environment. Experts have introduced circular design and construction methods to address the challenges posed by environmental issues. These methods include 'design for demolition' and 'design for modularity' along with constructing strategies like 'material banks and 'implementation of procedures. The focus of these design strategies is on evaluating building materials at their end-of-life stage to minimize resource consumption by reintegrating them into the production cycle. Conversely construction related techniques aim at reducing reliance on resources. This study evaluates these approaches in terms of their effectiveness in enhancing resilience, within the built environment.

Keywords: *adoption of efficient processes, design for demolition, design for modularity, material banks, resilience of the built environment.*

Introduction

In light of the growing environmental challenges we are facing, ensuring the resilience and adaptability of our cities and communities has become a top priority. Resilience now involves not just the strength and flexibility of urban systems, buildings and neighborhoods, but also their capacity to adjust and flourish in a changing environment. The built environment consists of various components such as infrastructure, structures and interconnected networks that are vital for urban operations. With urban areas expanding and grappling with diverse pressures linked to climate change, limited resources and population growth, bolstering resilience is essential for sustaining urban life.

This research explores different ecological design and building techniques that aim to strengthen the durability of constructed structures. These methods go beyond just reacting to issues and instead focus on proactive ways to combine sustainability with enhancing durability. The main emphasis is on creative design methods like "design for deconstruction" and "design for adaptability," as well as building techniques such as "material repositories" and the "use of effective procedures." These approaches play a crucial role in advocating for sustainability and reducing the negative effects of urban growth on nature.

The main goal of this study is to assess how certain ecological design and construction methods can enhance the resilience of the built environment. By integrating sustainable approaches across all stages of construction projects, from inception to demolition, this research seeks to showcase how these methods can help address environmental issues and promote a sustainable urban development.

This study delves into a thorough analysis of two important design approaches: (1) *Design for Demolition* and (2) *Design for Modularity*. As well as two crucial construction methods: (1) *Material Banks* and (2) *Adoption of Efficient Processes*. The assessment covers different aspects of resilience, such as physical, social, economic and environmental factors, to gain a holistic insight into how these strategies could affect resilience of the built environment.

This research holds importance as it fills a void in existing studies by offering a comprehensive examination of how ecological design and building techniques can improve the resilience of the built environment. The results are anticipated to provide useful perspectives for city planners, designers, decision makers and individuals engaged in urban growth, assisting them in making well informed choices that support sustainability and resilience goals.

In a world where cities are growing rapidly and encountering new environmental obstacles, the strength of our buildings and infrastructure is more important than ever. This research seeks to discuss and confirm eco-friendly building and design methods that not only tackle current environmental issues but also encourage lasting sustainability and toughness. Our goal with this study is to play a part in developing urban areas that are resilient, flexible and environmentally friendly, ready to withstand whatever challenges lie ahead.

Resilience in the Built Environment

Resilience within urban infrastructure plays a crucial role in dealing with the ability of cities, buildings and communities to endure, adjust to and recover from different challenges and disasters. This idea becomes more important given the impact of climate change, urban growth and other evolving forces on cities worldwide. Exploring the resilience of urban infrastructure involves looking at various aspects such as physical strength, social cohesion, economic stability and environmental sustainability. Each of these elements provides a comprehensive view of creating and sustaining resilient urban environments.

Physical and Structural Resilience

Resilience in the physical environment pertains to buildings and infrastructure's ability to endure and remain operational amidst natural disasters like earthquakes, floods or artificial incidents. It encompasses strong construction methods, the utilization of resilient materials and design strategies that can adjust to varying circumstances and pressures (Soust Verdaguer, 2015; Zatta et al., 2023).

Social and Community Resilience

In society, resilience refers to how communities can bounce back from disasters by using flexible social methods to uphold and reconstruct community structures and connections. This encompasses good communication, community involvement and social connections that can gather resources and aid collaborative recovery endeavors (Giovanni & Chelleri, 2017; Haigh & Amaratunga, 2010).

Economic Resilience

In terms of the economy, resilience refers to how well an economic system can handle the effects of a major event, reduce financial damage and bounce back quickly. This involves spreading out different economic activities, ensuring there are enough funds for recovering from disasters and keeping people employed even in times of crisis (Giovanni & Chelleri, 2017; Haigh & Amaratunga, 2010).

Environmental Resilience

In terms of the environment, building resilience in urban areas means implementing methods that improve sustainability and ecological balance. This entails incorporating green areas, sustainable water and waste management systems and energy efficient structures to lessen environmental harm and boost the ability to adapt to environmental shifts (Soust Verdaguer, 2015; Zatta et al., 2023).

Integration and Adaptation

An important aspect of being resilient is to blend these aspects together, making sure that physical strength, community unity, financial security and environmental sustainability are all taken into account in a comprehensive way. This holistic approach is essential for creating flexible plans that tackle not just immediate consequences but also the long-term issues brought about by urban growth and climate shifts (Gallo & Romano, 2018; Kirillov et al., 2013; Rözer et al., 2022; Soust Verdaguer, 2015; Zatta et al., 2023).

Continuous Learning and Improvement

Resilience is more than just a fixed quality; it's an ever evolving journey that includes constant learning, adjustment and progress. It involves regularly evaluating, updating planning strategies and design norms and integrating new technologies and methods to boost the overall resilience of our constructed surroundings (Kirillov et al., 2013; Soust Verdaguer, 2015; Zatta et al., 2023).

Creating resilience within the built environment involves developing systems that are not only sturdy and able to endure unexpected events but also flexible, environmentally friendly, and capable of evolving to address new obstacles and possibilities. This holistic method to resilience promotes not only survival but also the flourishing of societies when confronted with both anticipated and unforeseen difficulties.

Design for Disassembly

The concept of Design for Disassembly (DfD) focuses on creating products in a way that makes it simple to take them apart and recover their components and materials when they reach the end of their life cycle. This approach is especially important in industries like construction and product design as it helps minimize waste and improve the ability to recycle materials.

Principles of Design for Disassembly

The core principles of Design for Disassembly (DfD) revolve around various essential strategies aimed at facilitating the effortless disassembly of products and structures:

Standardization of Components*:* Utilizing standard components in various products or designs streamlines the process of taking things apart, as it reduces the need for a wide range of tools and steps to disassemble them (Kissi et al., 2019b, 2019a).

Use of Mechanical Fasteners: Using mechanical connections instead of glue or permanent welding makes it simpler to take things apart and put them back together, which helps in recycling components (Kissi et al., 2019b, 2019a).

Documentation of Materials and Methods: Effective documentation plays a key role in recognizing the materials utilized and the techniques employed during assembly, essential for efficient disassembly and recycling (Kissi et al., 2019a, 2019b).

Modular Design: Creating products or structures in separate modular parts can significantly improve the convenience of dismantling and reusing the modules in the future (Errante & Capua, 2021).

Benefits of Design for Disassembly

Implementing Design for Disassembly (DfD) provides various environmental and financial advantages, as highlighted by Crowther (2022) and Incelli and Cardellicchio (2021).

Waste reduction: By promoting the repurposing and recycling of materials, Design for Disassembly (DfD) effectively reduces the amount of waste produced at the conclusion of a product's lifespan.

Resource Efficiency: By encouraging the effective utilization of resources through recycling and repurposing materials, it helps decrease the need for new resources and lessens the environmental repercussions linked to extracting and processing materials.

Economic Savings: Reusing and recycling materials can result in considerable cost savings when it comes to buying materials and managing waste.

Flexibility and Adaptability: The principles of Design for Disassembly (DfD) aid in modifying buildings and products to accommodate new purposes or technological advancements, prolonging their usability and improving their sustainability.

Challenges of Design for Disassembly

Despite the advantages it offers, implementing Design for Disassembly (DfD) also encounters various challenges:

Complexity in Design: Adding disassembly features to the design process can complicate things, requiring more planning and potentially increasing initial costs (Crowther, 2022).

Market and Cultural Obstacles: Industry stakeholders might resist due to the inertia of existing practices and the cost implications of embracing new design approaches (Crowther, 2022).

Technical Constraints: Some materials or design setups may not easily align with DfD principles, limiting their effectiveness in certain scenarios (Ruan et al., 2024).

In essence, Designing for Disassembly plays a vital role in promoting sustainable practices in design and building. It comes with notable advantages such as cutting down on waste, optimizing resources and saving money. However, it also brings about obstacles that require creative design remedies and a shift in industry norms.

Design for Modularity

Design modularity involves breaking down intricate systems into smaller, independent modules that can be created, adjusted, replaced or swapped between different systems. This method emphasizes dividing a system into manageable modules with standardized interfaces to enhance flexibility, adaptability and scalability. The idea of modularity is widely used in industries such as automotive, electronics, manufacturing and urban logistics. It is also making its way into ecological design and construction practices according to several studies (Hackl et al., 2020; Kubota et al., 2013; Pakkanen et al., 2018; Sanchez & Shibata, 2018).

Benefits of Design for Modularity

The advantages of incorporating modularity into ecological design and construction are numerous. To begin with, modularity enables customization and a wider range of product options, making it beneficial for meeting various user requirements and adjusting to specific environmental factors in the area. This flexibility enhances the durability of the constructed environment since modular designs can be adjusted easily to withstand different weather conditions (Kubota et al., 2013).

Furthermore, breaking down projects into modular components can result in cost and time savings during the development and building phases. Standardizing modules enables economies of scale and reduces the design and assembly time significantly. This streamlined process enhances the sustainability of construction ventures by reducing waste and optimizing resource utilization, as noted by Balkenende and Bakker (2015) and Kubota et al. (2013).

Another benefit of modularity is its role in promoting the eco friendliness of products through enhancing their recyclability and facilitating the repurposing of parts or products. When products are designed for easy disassembly, it becomes simpler to separate materials during end-of-life stages, ultimately contributing to the concept of a circular economy (Balkenende & Bakker, 2015).

Modularity plays a key role in improving operational flexibility, especially in microgrids. It contributes to the system's strength and dependability by allowing for the isolation and management of individual modules. This capability helps prevent widespread failures and enables better control and maintenance within the larger system (Maigha & Enslin, 2018).

Challenges of Design for Modularity

While modularity in ecological design and construction offers advantages, there are obstacles that come with its implementation. One significant challenge involves relying more on suppliers, especially when modules come from different sources. This dependency can limit innovation since suppliers might struggle to tailor their products to fit the unique requirements of a modular system (Kubota et al., 2013).

A different issue lies in the requirement for a strong design approach capable of managing the intricacies of modular systems. Existing engineering design methods might not be enough to achieve the usual advantages associated with modularity and reusing designs. Companies need to emphasize retrieving knowledge and overseeing the design process to address these obstacles (Pakkanen et al., 2018).

In building modular systems, it's crucial to strike a balance between standardization and customization. Going too far with standardization may result in lower performance than holistic design methods, whereas excessive customization can diminish the advantages of modularity (Agrawal et al., 2013).

Material Bank

In the construction industry, a "Material Bank" serves as a repository for different construction materials, their details and relevant information. It can be likened to a library or a bank where materials and their data are stored and handled instead of money or books. The main goal of a material bank is to streamline resource utilization, encourage material recycling and reusability and endorse sustainable construction methods (Guerra et al., 2021).

The opportunity for material banks has significantly increased thanks to advancements in information technology. These collections can now cover a variety of construction materials and parts. Cocco and Ruggiero (2023) have led the way in this area by creating a digital database that streamlines the adoption of the material repository idea. Furthermore, Casey (2024) has introduced an innovative approach to labeling materials, akin to "passports," enhancing the tracking and reuse of materials.

However, by limiting the scope of materials that banks deal with only to building materials, their full potential remains untapped. Cai and Waldmann (2019) have broadened this concept to include building elements, pointing out that reusing pre-assembled parts can significantly reduce the consumption of resources and time needed for reuse without the need for disassembly and reassembly. Jayasinghe and Waldmann (2020) have explored how Building Information Modelling (BIM) software can promote the idea of material banks and improve the reuse of building components. BIM offers in-depth digital models of buildings together with extensive information on the building materials. Material passports, which are comprehensive records of materials that may be updated during the life of the building, cannot be created or managed without this capacity (Junussova et al., 2024). BIM can play a crucial role in strategic planning for deconstruction as an alternative to demolition. Through the utilization of Building Information Modelling (BIM), stakeholders can generate comprehensive deconstruction plans that enable them to ascertain the specific elements that can be rescued and repurposed in subsequent projects (Sudarsan & Gavali, 2023).

Application of Material Bank

The use of material banks in building projects has many dimensions. Essentially, it acts as a centralized hub for storing data on various materials that can be accessed to assist in the planning, construction and upkeep of structures and infrastructure. For example, a material repository can assist in pinpointing appropriate materials that meet particular environmental or structural standards, thereby facilitating the selection process during the planning stage of a project.

Resource Efficiency: Through the utilization of a material bank system, construction projects have the potential to cut down on waste by repurposing materials sourced from dismantled locations or leftovers from prior projects. This approach not only aids in cost savings but also lessens the environmental repercussions linked to the creation and elimination of construction materials.

Sustainability and Environmental Impact: Material repositories promote the utilization of recycled and environmentally sustainable materials. Through offering insights into material life cycles and eco friendliness, these repositories facilitate the construction of eco conscious buildings that adhere to green construction guidelines.

Innovation and Quality Control: Material banks can support creativity by offering information on fresh and substitute materials. Additionally, they guarantee quality assurance by keeping track of material effectiveness and adherence to industry regulations.

Adoption of Efficient Processes

The building sector plays a major role in harming the environment, but it also has the opportunity to improve the durability of structures by using eco-friendly design and construction methods. It is important to embrace effective practices in construction to bring about this change. Here, we examine the different approaches and techniques created and put into action to enhance productivity and eco friendliness in building projects.

Lean Construction and Artificial Intelligence as Examples of Efficient Process Adoption

Lean construction strategies focus on reducing waste and increasing value through process optimization. Incorporating artificial intelligence techniques in lean construction can greatly improve project management results, enhancing cost effectiveness and timeline efficiency (Velezmoro-Abanto et al., 2024). By leveraging AI, especially machine learning and artificial neural networks, construction projects can benefit from reduced delays, enhanced collaboration, and decreased expenses (Velezmoro-Abanto et al., 2024). The collaboration between lean construction and AI not only enhances productivity but also aligns with ecological design principles by emphasizing resource efficiency and minimizing environmental impact.

Sustainable and Technological Advancements as Examples of Efficient Process Adoption

Sustainable building methods are more and more being combined with efficient building principles. The viewpoints of stakeholders are crucial in examining and putting into practice sustainable efficient building strategies (Jamil & Fathi, 2016). Creating models using interpretive structural modeling (ISM) technique assists in pinpointing crucial factors for successful implementation of efficient building, customized to specific socio cultural and operational settings (Olubunmi, 2020; Sarhan et al., 2019). These models aid in grasping the connections among different factors and devising plans for successful execution.

Barriers and Drivers of Change

Efficient construction practices are influenced by various factors that drive or hinder their adoption. Making organizational changes is crucial for increasing the use of prefabrication and other efficient methods in construction (Wong et al., 2017). Understanding these factors is important to develop effective strategies that can help overcome resistance and encourage the implementation of sustainable building practices (Gao et al., 2020). For example, a lack of expertise in utilizing lean tools and principles poses a significant challenge, while improved time management and standardized processes serve as key motivators (Adhi & Muslim, 2023).

Evaluation of Concepts for Their Possible Impacts on Resilience

The resilience of the built environment is a complex idea that covers the capacity of buildings, systems and communities to endure, adjust to and bounce back from different challenges and crises. This section examines the possible effects of Design for Disassembly (DfD), Design for Modularity, Material Bank and the Implementation of Efficient Procedures on the resilience of the built environment.

Possible Impacts of Design for Disassembly (DfD) on Resilience

<u>Enhanced Recovery and Adaptability:</u> Design for Disassembly enables the simple separation and retrieval of parts and materials at the conclusion of a product's lifespan. This flexibility proves vital in situations following disasters, where swift recovery and reconstruction of the constructed surroundings become imperative (Andrade & Bragança, 2019; Kissi et al., 2019b).

Waste Reduction and Resource Efficiency: By encouraging the repurposing and recycling of materials, DfD plays a role in decreasing waste production and promoting the sustainable utilization of resources, crucial for ensuring the long-term durability of urban systems (Andrade & Bragança, 2019; Kissi et al., 2019b).

Economic Resilience: Communities can bounce back faster from economic crises triggered by disasters with the financial benefits of cutting down on material expenses and improving waste management, as suggested by Andrade and Bragança (2019) and Kissi et al. (2019b).

Design Complexity: Integrating DfD features in post disaster reconstruction efforts might pose challenges due to the need for extra resources and specialized knowledge, potentially hindering progress (Andrade & Bragança, 2019; Kissi et al., 2019b).

Market and Cultural Barriers: Resistance from individuals in the industry who are hesitant to embrace new approaches could delay the implementation of DfD, which might impede progress in building resilience (Andrade & Bragança, 2019).

Possible Impacts of Design for Modularity on Resilience

Customization and Adaptability: Modular structures have the flexibility to adapt to various weather conditions, improving the durability of buildings in different climates (Andrade & Bragança, 2019; Kubota et al., 2013).

Operational Flexibility: Being able to handle separate components in a bigger system can help avoid chain reactions of failures and enable accurate management and upkeep, enhancing the resilience of city systems as a whole (Andrade & Bragança, 2019; Kubota et al., 2013).

Supplier Dependence: Relying more on suppliers for modular parts could lead to potential weaknesses, like supply chain interruptions that might impact the resilience of building projects (Andrade & Bragança, 2019; Balkenende & Bakker, 2015).

Balance between Standardization and Customization: Achieving a proper equilibrium is essential to guarantee that the modularity doesn't hinder effectiveness or diminish the advantages of standardization (Andrade & Bragança, 2019; Balkenende & Bakker, 2015).

Possible Impacts of Material Bank on Resilience

Resource Efficiency and Sustainability: Material bank plays a crucial role in cutting down on waste by promoting the recycling of materials, thus bolstering the environmental sustainability of cities (Andrade & Bragança, 2019; Guerra et al., 2021).

Innovation and Quality Control: Material banks play a crucial role in promoting innovation and guaranteeing that construction materials adhere to industry regulations, thus safeguarding the resilience of our built environment (Andrade & Bragança, 2019; Guerra et al., 2021).

Implementation Complexity: Successfully implementing material banks relies on strong information systems and collaboration among various parties, which can pose difficulties in the aftermath of a calamity (Andrade & Bragança, 2019; Guerra et al., 2021).

Possible Impacts of Adoption of Efficient Processes on Resilience

Lean Construction and AI: The combination of lean construction methods with AI has the potential to boost project management results, ultimately improving cost effectiveness and timeliness, essential for swiftly rebuilding resilient infrastructure (Andrade & Bragança, 2019; Velezmoro Abanto et al., 2024).

Prefabrication and Modular Construction: These approaches help save time, cut costs, and minimize waste, in line with sustainable design principles and boosting the resilience of building projects (Andrade & Bragança, 2019; Velezmoro Abanto et al., 2024).

Organizational Change: The implementation of innovative construction techniques necessitates substantial organizational adjustments, posing a challenge to enhancing resilience if not handled adeptly (Andrade & Bragança, 2019).

Knowledge and Skill Barriers: Insufficient understanding and proficiency in utilizing modern tools and concepts may impede the implementation of effective procedures, impacting the resilience of the built environment (Andrade & Bragança, 2019).

Conclusion

This study extensively examined different ecological design and building techniques that aim to improve the resilience of the built environment. By delving into ideas like Design for Disassembly (DfD), Design for Modularity, Material Banks and the Implementation of Efficient Procedures, this research has underscored how these approaches can greatly influence the resilience and eco friendliness of urban systems.

Designing for disassembly (DfD) has been a game changer in boosting the recovery and adaptability of building parts, making post disaster reconstruction quicker while cutting down on waste and resource use. Opting for modular design allows for more customized solutions and operational flexibility, essential for tackling various environmental challenges and preventing breakdowns during emergencies. Material banks play a key role in optimizing material usage, promoting sustainability by enabling the reuse and recycling of construction materials and sparking innovation by providing insights into alternative materials. Adoption of the efficient processes like lean construction practices and incorporating artificial intelligence into project management can significantly enhance outcomes in terms of cost efficiency and project timelines, crucial elements for resilience in challenging situations.

The methods mentioned are not just technical fixes but represent changes that blend environmental, economic, and social aspects. They help improve the construction industry sustainability and strengthen urban resilience, which is vital given the ongoing global environmental shifts and urban growth challenges. Implementing these approaches can result in notable environmental advantages like decreased emissions, reduced energy use and less waste generation.

Although the advantages of these approaches are evident, putting them into practice encounters obstacles such as technological constraints, reluctance from the market and the necessity for increased expertise among industry participants. Moving forward, research should concentrate on creating stronger tools and methods to address the design and implementation hurdles linked to these approaches, boosting involvement and education among stakeholders to encourage wider acceptance of sustainable methods and investigating how these approaches can be integrated into larger urban planning and policy frameworks to enhance their influence on urban resilience.

References

Adhi, A. B., & Muslim, F. (2023). Development of stakeholder engagement strategies to improve sustainable construction implementation based on lean construction principles in Indonesia. *Sustainability*.

Agrawal, T., Sao, A. D., Fernandes, K. J., Tiwari, M. K., & Kim, D.-Y. (2013a). A hybrid model of component sharing and platform modularity for optimal product family design. *International Journal of Production Research*, *51*, 614-625.

Agrawal, T., Sao, A. D., Fernandes, K. J., Tiwari, M. K., & Kim, D.-Y. (2013b). A hybrid model of component sharing and platform modularity for optimal product family design. *International Journal of Production Research*, *51*, 614-625.

Anastasiades, K., Dockx, J., van den Berg, M., Rinke, M., Blom, J., & Audenaert, A. (2023). Stakeholder perceptions on implementing design for disassembly and standardisation for heterogeneous construction components. *Waste Management & Research*, *41*(8), 1372-1381.

Andrade, J. B., & Bragança, L. (2019). Assessing buildings' adaptability at early design stages. *IOP Conference Series: Earth and Environmental Science*, *225*.

Arashpour, M., & Wakefield, R. R. (2020). *Using BIM for multi-trade prefabrication in construction*.

Arisya, K. F., & Suryantini, R. (2021). Modularity in design for disassembly (DfD): exploring the strategy for a better sustainable architecture. *IOP Conference Series: Earth and Environmental Science*, *738*(1), 012024.

Balkenende, A. R., & Bakker, C. A. (2015). Developments and challenges in design for sustainability of electronics. *Proceedings of ISPE International Conference on Concurrent Engineering*.

BAMB Project (n.d.). *BAMB - building as material banks*. https://www.bamb2020.eu/

Cai, G., & Waldmann, D. (2019). A material and component bank to facilitate material recycling and component reuse for a sustainable construction: concept and preliminary study. *Clean Technologies and Environmental Policy*, *21*(10), 2015-2032.

Casey, T. (2024). *How the circular economy can transform buildings into "material banks"*.

Chippagiri, R., Brás, A., Sharma, D., & Ralegaonkar, R. V. (2022). Technological and sustainable perception on the advancements of prefabrication in construction industry. *Energies.*

Chirayu, Y., & Yashika, G. (2023). Design for disassembly in architecture. *International Journal of Scientific Research in Engineering and Management*, *7*(4), 1-8.

Cocco, P. L., & Ruggiero, R. (2023). From rubbles to digital material bank: a digital methodology for construction and demolition waste management in post-disaster areas. *Environmental Research and Technology*, *6*(2), 151-158.

Crowther, P. (2022). Exploring the principles of design for disassembly through design-led research. *IOP Conference Series: Earth and Environmental Science, 1101*.

Dinis, P., & Veiga, I. (2022). Disassembly objects: the importance of materials in product design education. *Human Dynamics and Design for the Development of Contemporary Societies*, *25*(25).

Errante, L., & Capua, A. D. (2021). Design for disassembly and the rehabilitation of public housing stock: a case study. *TECHNE - Journal of Technology for Architecture and Environment*.

Gallo, P., & Romano, R. (2018). Rethinking the edge: the built environment and resilience in the informal city. *Journal of Technology for Architecture and Environment*, *15,* 279-290.

Gao, Z., Aslam, M., & Smith, G. R. (2020). *Strategies to increase adoption rate of lean construction*.

Giovanni, G. D., & Chelleri, L. (2017). *Sustainable disaster resilience? Tensions between socio-economic recovery and built environment post-disaster reconstruction in Abruzzo (Italy)*.

Guerra, B. C., Shahi, S., Mollaei, A., Skaf, N., Weber, O., Leite, F., & Haas, C. (2021). Circular economy applications in the construction industry: a global scan of trends and opportunities. *Journal of Cleaner Production*, *324,* 129125.

Hackl, J., Krause, D., Otto, K. N., Windheim, M., Moon, S. K., Bursac, N., & Lachmayer, R. (2020). Impact of modularity decisions on a firm's economic objectives. *Journal of Mechanical Design*.

Haigh, R., & Amaratunga, D. G. (2010). An integrative review of the built environment discipline's role in the development of society's resilience to disasters. *International Journal of Disaster Resilience in The Built Environment*, *1*, 11-24.

Incelli, F., & Cardellicchio, L. (2021). Designing a steel connection with a high degree of disassembly: a practice-based experience. *TECHNE - Journal of Technology for Architecture and Environment*.

Jamil, A. H. A., & Fathi, M. S. (2016). The integration of lean construction and sustainable construction: a stakeholder perspective in analyzing sustainable lean construction strategies in Malaysia. *CENTERIS/ProjMAN/HCist*.

Jayasinghe, L. B., & Waldmann, D. (2020). Development of a BIM-based web tool as a material and component bank for a sustainable construction industry. *Sustainability, 12*(5).

Joensuu, T., Edelman, H., & Saari, A. (2020). Circular economy practices in the built environment. *Journal of Cleaner Production*, *276*, 124215.

Junussova, T., Nadeem, A., Kim, J. R., & Azhar, S. (2024). Key drivers for BIM-enabled materials management: insights for a sustainable environment. *Buildings*, *14*(1).

Karen, C. (n.d.). *Loblolly House / Kieran Timberlake*. Archdaily.

Kirillov, I. A., Metcherin, S. A., & Klimenko, S. V. (2013). Towards multi-hazard resilience as a new engineering paradigm for safety and security provision of built environment. *Transactions of Computing Science*, *18*, 121-136.

Kissi, E., Ansah, M. K., Ampofo, J., & Boakye, E. (2019a). *Of the principles of design for disassembly*.

Kissi, E., Ansah, M. K., Ampofo, J., & Boakye, E. E. (2019b). Critical review of the principles of design for disassembly. *Modular and Offsite Construction (MOC) Summit Proceedings*.

Kubota, F. I., Gontijo, L. A., & Miguel, P. A. C. (2013). *Design modularity: identification of benefits and difficulties through a bibliographical analysis in the perspective of automotive assemblers and suppliers.*

Maigha, M., & Enslin, J. H. R. (2018). Educating microgrids using planning tools-interactive case studies and lessons learned. *Proceedings of 9th IEEE International Symposium on Power Electronics for Distributed Generation Systems*, 1-6.

Olubunmi, A. (2020). *Framework for the implementation of lean construction strategies using ISM technique: a case of Saudi construction industry*.

Pakkanen, J., Juuti, T., & Lehtonen, T. (2018). Identifying and addressing challenges in the engineering design of modular systems – case studies in the manufacturing industry. *Journal of Engineering Design*, *30*, 32-61.

Peng, C., Hao, P., & Su, P. (2014). The research and engineering application of a New Hardfill Cofferdam in Shatuo Hydropower Station. *Applied Mechanics and Materials*, 638-640.

Rözer, V., Mehryar, S., & Surminski, S. (2022). From managing risk to increasing resilience: a review on the development of urban flood resilience, its assessment and the implications for decision making. *Environmental Research Letters*, *17*.

Ruan, G., Filz, G. H., & Fink, G. (2024). Special IASS 2024 planar rectangular slide-in reciprocal frame system using salvaged timber and wooden nails. *Journal of the International Association for Shell and Spatial Structures*.

Sanchez, R., & Shibata, T. (2018). Modularity design rules for architecture development: theory, implementation, and evidence from the development of the Renault–Nissan Alliance “common module family” architecture. *Journal of Open Innovation: Technology, Market, and Complexity*.

Sarhan, J. G., Xia, B., Fawzia, S., Karim, A., Olanipekun, A. O., & Coffey, V. (2019). Framework for the implementation of lean construction strategies using the interpretive structural modelling (ISM) technique. *Engineering, Construction and Architectural Management*.

Soust-Verdaguer, B. (2015). *Towards the definition of new tools of design and environmental assesments performance in built environment*.

Tina, V. (2013). *NASA sustainability base*. Gb&d.

Velezmoro-Abanto, L., Cuba-Lagos, R., Taico-Valverde, B., Iparraguirre-Villanueva, O., & Cabanillas-Carbonell, M. (2024). Lean construction strategies supported by artificial intelligence techniques for construction project management—a review. *International Journal of Online and Biomedical Engineering*.

Wong, P. S. P., Zwar, C., & Gharaie, E. (2017). Examining the drivers and states of organizational change for greater use of prefabrication in construction projects. *Journal of Construction Engineering and Management*, *143*, 04017020.

Yi-bing, L. (2006). Construction of traffic accident reconstruction teaching material bank. *Experimental Technology and Management*.

Zatta, E., Condotta, M., Revellini, R., & Tatano, V. (2023). Delivering sustainability in the Italian N-E built environment and construction sector: a conceptual research framework. *Buildings*.

Construction Waste Management and Standardization Relation: A Case Study

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Abstract

Lean thinking focuses to minimize/eliminate waste while maximize value. Waste in the construction industry can be defined as evitable and inevitable activities during the project life cycle. Waste is occurred as physical as labor, materials, equipment or non-physical as quality, time, and cost. On the other hand, waste could be caused by different reasons such as building production processes, stakeholders, force majeure. Standardization, which is used to clarify the working process and reduce of variation etc., could be evaluated as one of the strong ways to manage both type waste. In this study, effect of products/components standardization is discussed in terms of the waste management with a case study. A breakdown structure is composed to determine the products/components which are used in this case study. According to this case study, the effects of standardized products/components are evaluated in terms of waste management. In addition, the benefits, challenges, and availability of standardization are evaluated.

Keywords: *construction industry, construction waste, lean approach, standardization, waste management.*

Introduction

Lean is a systematic approach which has generic principles, techniques and tools that aims to identify and eliminate waste while maximizing the value. Lean thinking leads to the five principles as value, value stream, flow, pull and perfection (Womack & Jones, 1996). The main aim of lean thinking is to achieve a lean production system. To reach and create a lean production system, the lean tools and techniques are integrated through the production process on the base of lean principles.

With the manufacturing industry becoming increasingly efficient with lean thinking, the lean approach started to be examined in the construction industry in the 1990s. The concept of "lean construction" started to emerge with the idea that the principles of lean thinking could be applied not only in the manufacturing industry but also in the construction industry to eliminate waste and create value. Lean principles start with defining value and value stream. The second principle of lean focuses creating a value stream mapping, after defining value. In this value stream mapping step, it is identified all the production process steps considering the idea of waste elimination (Womack & Jones, 2003). When value is described well, waste can be managed to minimize and eliminate. Waste could be occurred as physical as labor, materials, equipment or non-physical as quality, time, cost. On the other hand, waste could be caused by different reasons such as building production processes, stakeholders, force majeure.

Value adding activities are closely related with the final form, feature, or function of the product/service that the customer is willing to pay for (O'Connor & Swain, 2013). Activities that do not create value are defined as activities that cause waste in terms of lean thinking's perception of value and waste. Non-value adding activities are grouped with evitable wastes and inevitable wastes. According to O'Connor and Swain (2013), evitable wastes are generally accidents, delay, waiting, rework, over-ordered materials, damaged materials, poor payment systems, multiple handling systems, selected tender method etc. in the construction industry. On the other hand, inevitable wastes are generally procurement, taxes, insurance, logistics, accounting, cost estimating, commercial management etc. in the construction industry. The inevitable wastes can be thought of as tasks which should be completed to realize value. As a result of this, it should be cared that the inevitable wastes could be minimized whereas the evitable wastes could be eliminated.

Eliminating waste in a process is one of the top priorities in the lean construction, too as lean manufacturing. (Mao & Zhang, 2008). So, managing of both physical wastes such as material, labor and equipment and non-physical wastes such as cost, time and quality started to be one of the crucial issue that should be cared during the building life cycle since the construction industry generates immense amounts of waste.

The objective of this study was to investigate the impact of standardization on waste in the construction process. So, the construction process of a completed prefabricated construction project was examined to determine the amount of waste generated. The products/components employed in prefabricated construction were categorized as those produced off-site and on-site. The objective was to ascertain the quantity of waste generated by each group and to investigate the impact of the utilization of standardized products/components on the formation of waste at the construction site.

Construction Waste Management and Standardization Relation

Standards are used to the reduction of variation and error correction, improved safety, facilitate communication, visibility problems, assistance in training and education, increasing labor discipline, facilitating the response to the challenges and clarification of the working procedures (Košturiak et al., 2010). Imai (2005) classified the standards into two type as management standards (related with the management of staff and administrative purpose) and operating standards (related with how employees carry out their work).

Construction activities generally have process control and improvement problems such as variability, complexity, transparency, and benchmarking (Koskela, 1992). Standardization is the wide use of components, parts, procedures, or processes in which there is regularity, repetition, and a successful practice and predictability (Gibb & Isack 2001, Pasquire & Gibb, 2002). Gibb and Isack (2001) thought that the process standardization reduces costs and has a positive impact on processes. On the other hand, products/components standardization can minimize the cost whereas minimize the lead-in time and maximize quality and operational benefits (Gibb & Isack, 2001, Li et al., 2008, Pasquire & Gibb, 2002). Aki and Harri (2014) discussed the main characteristics of process and products/components standardization on their study. According to this study, organizational interfaces, more predictable on-site activities, increased productivity, less waste, less disruption, quality benefits, cost benefits, process benefits, people/operational & time & design benefits are the main characteristics of standardized process whereas track record, increased productivity due to familiarization, less waste, use of the same products/components in follow on projects, reduced lean in times, predictable and measurable quality, off-site inspection, available replacement parts and people/operational benefits are the characteristics of standardized products and components.

Prefabrication, which includes preassembly and modularization, is considered as a potential method to assist the construction development (Koskela, 2000). Aki and Harri (2014) specified that there is a potential way to implement lean principles, or at least some of them by prefabrication. In addition that, according to Tam et al. (2007)'s study, it is calculated that material waste generation and its cost can be minimized to 84.7% by reducing up on-site production. According to Gibb (2000), the benefits of prefabrication can be maximized with the maximization use of the standardized processes and products/components.

A Case Study: A Prefabricated Project in Istanbul

A prefabricated construction project, constructed in Istanbul, is analyzed in this study to identify products/components waste during the construction process in terms of standardized products/components. This case study is a part of the work which is supported by Scientific Research Projects Department of Istanbul Technical University with Project Number: 44178, Project Code: MGA-2022-44178 and Project Name "Calculation of Waste Index for Material Waste Management in Turkish Construction Industry: Prefabricated Buildings Sample".

Table 1. Project tag of "Istanbul Prefabricated Project".

Project Specifications	**Description**
Project Name	Istanbul Prefabricated Project
Project Location	Istanbul, Türkiye
Building Types	Prefabricated Buildings
Project Type	Construction Site Buildings
Gross Area (sqm)(m^2)	Staff Office (249) + Dining Hall (243) + Staff Dormitory (303) + Worker Dormitory (534) = 1329
Project Completion Status	100%
Project Completion Year	2023
Number of Buildings	4
Number of Floors	Staff Office (1), Dining Hall (1), Staff Dormitory (1), Worker Dormitory (1)

The project, which is evaluated in terms of construction waste management and standardization in this study, contains 4 different type of building as staff office building, dining hall building, staff dormitory and worker dormitory. The gross area of the prefabricated project, completed in 2023, is 1329 sqm (Table 1).

The data of this constrution project was obtained through face-to-face and online meetings with the authorized person(s) responsible for the projects in the relevant company. The data of each building received for “Istanbul Prefabricated Project” were as architectural application projects, electrical projects, project material list (general materials and quantity-unit list), purchase forms and surplus materials. When the data received from the company was analyzed, it was understood that the data in the company's possession was not data collected in accordance with the determination of waste in the construction process. To analyze the data of completed prefabricated project, the data received from the authorized person(s) responsible for the projects in the relevant company was reclassified in accordance with the purpose of the research in line with the opinions of the authorized person(s).

“Staff Office Ground Floor Plan” of the "Istanbul Prefabricated Project" is shown in Figure 1 whereas “Dining Hall Ground Floor Plan” is shown in Figure 2.

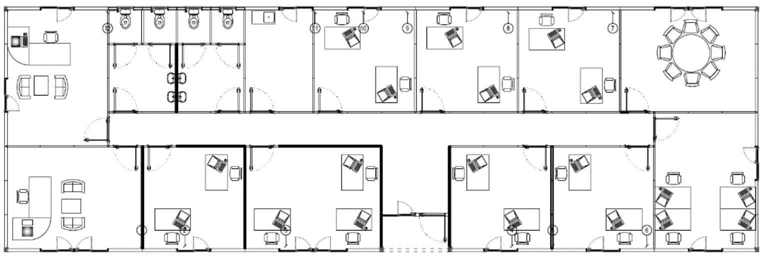


Figure 1: Staff office ground floor plan.

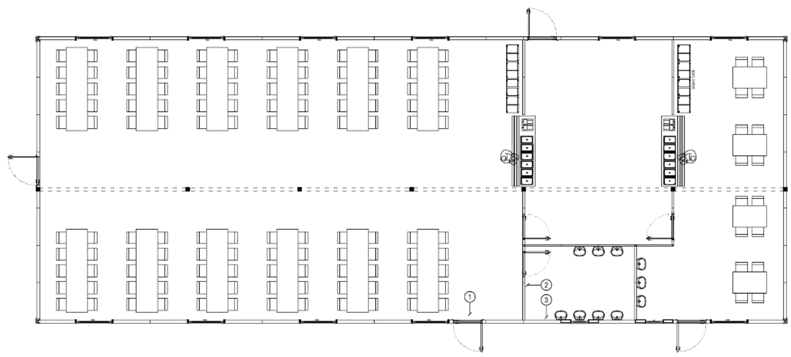


Figure 2: Dining hall ground floor plan.

“Staff Dormitory Ground Floor Plan” is shown in Figure 3 whereas “Worker Dormitory Ground Floor Plan” is shown in Figure 4. All these buildings have only one floor as ground floor with different gross areas as seen in Table 1.

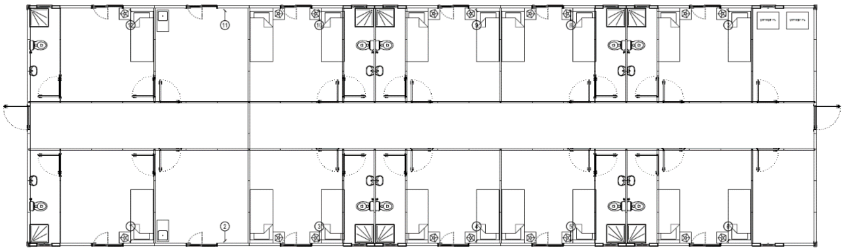


Figure 3: Staff dormitory ground floor plan.

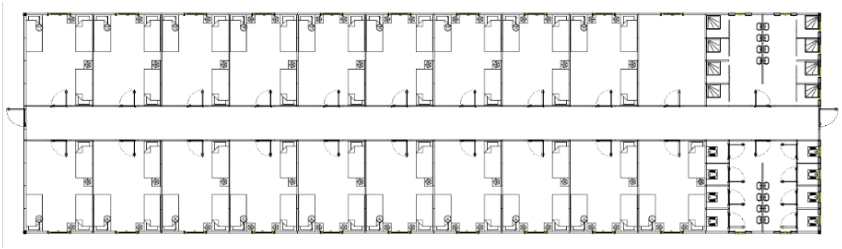


Figure 4: Worker dormitory ground floor plan.

According to the architectural projects, a production breakdown structure was created to categorize and figure out standardized products/components groups. According to the meetings with the authorized person(s) responsible for the projects in the relevant company, it is obtained that the mechanical works and a part of fine works do not belong to this company's responsibility. So, the production breakdown structure of "Istanbul Prefabricated Project" is specified according to the completed work packages by the company.

In this project, which contains 4 different buildings, 5 main work categories (rough works and fine works etc.) are composed for the production breakdown structure. These are rough works, roof and façade works, fine works, electrical works and fittings. The rough works are grouped into the basement, exterior wall bearing systems and profiles and interior wall bearing systems and profiles as seen in Figure 5.

PRODUCT BREAKDOWN STRUCTURE		
ROUGH WORKS	WALLS	BASEMENT (bottom frame etc.)
		EXTERIOR WALL BEARING SYSTEMS AND PROFILES (H Profiles, Corner Studs, Profiles etc.)
		INTERIOR WALL BEARING SYSTEMS AND PROFILES (Bottom frame, H Profiles, Omega Profiles, Corner Studs etc.)
	ROOF	ROOF BEARING SYTEMS AND ROOF TRUSS THICKNESS (Head and mid Trusses, Purlins etc.)

Figure 5: Rough works.

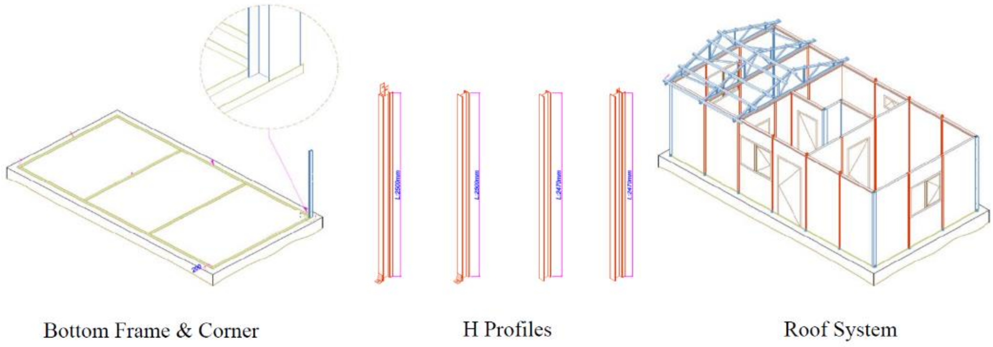


Figure 6: Standardized products/components of rough works.

When the rough construction products/components are checked, it is seen that all products/components in this group were implemented at the construction site. Because of being standardized products/components which are produced off-site and implemented at site completely, waste is not occurred in this group. In Figure 6, bottom frame, corner studs, H-profile types and roof system standard sized production are seen.

The roof and facade works are grouped into the roof covering, eave and fascia, rain downpipes and gutter and exterior wall exterior cladding as seen in Figure 7. It is seen that all products/components in this group were implemented at the construction site, too.

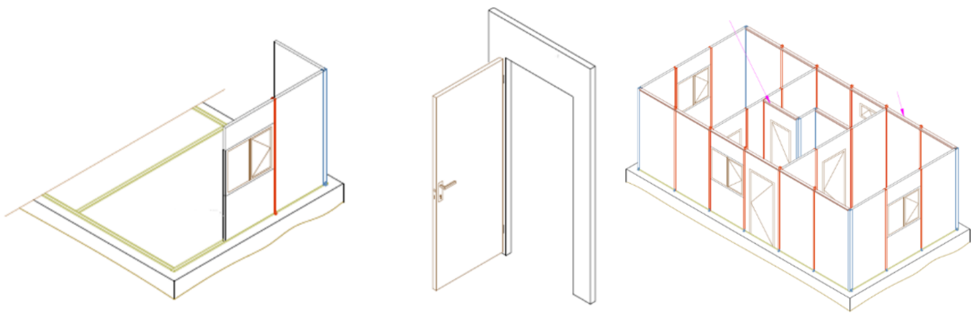
<table>
<tr><th colspan="3">PRODUCT BREAKDOWN STRUCTURE</th></tr>
<tr><td rowspan="4">ROOF AND FACADE WORKS</td><td rowspan="3">ROOF</td><td>ROOF COVERING
(Roofing Sheet, Trapezoidal Metal Sheet etc.)</td></tr>
<tr><td>EAVE AND FASCIA
(Eave Omega, Fascia Profiles etc.)</td></tr>
<tr><td>RAIN DOWNPIPES AND GUTTER
(Pvc Gutter, Stoper, Pvc Pipes etc.)</td></tr>
<tr><td>WALLS</td><td>EXTERIOR WALL-EXTERIOR CLADDING
(Pressed Panel Types)</td></tr>
</table>

Figure 7: Roof and facade works.

The fine works are grouped into the interior cladding, ceiling covering, exterior doors, interior doors and windows as seen in Figure 8. According to the meetings, it is seen that all products/components in this group were implemented at construction site, too. In Figure 9, windows & window panels, doors & door panels and interior & exterior panels' standard sized production are seen. These groups' products/components were produced off-site with the standard size and limited types of production, during the construction process waste was not occurred. The production process waste were not investigated because of being out of scope.

PRODUCT BREAKDOWN STRUCTURE		
FINE WORKS	WALLS	INTERIOR CLADDING (Pressed Panel Types)
	CEILING	CEILING COVERING (Gypsum Board)
	DOORS AND WINDOWS	EXTERIOR DOORS (Exterior Door Panel Types and Doors)
		INTERIOR DOORS (Interior Door Panel Types and Doors)
		WINDOWS (Window Panel Types and Windows)

Figure 8: Fine works.



Windows & Window Panels   Doors & Door Panels   Interior & Exterior Panels

Figure 9: Standardized products/components of fine works.

PRODUCT BREAKDOWN STRUCTURE		
ELECTRICAL INSTALLATION	WIRING	WIRING (Cable Types etc.)
	ELECTRICAL PANEL	FUSE & PANEL (Automats, Cutout Circuit Breakers, Leakage Relays, Fuse Panels etc.)
	SWITCHES, SOCKETS, LUMINARIES	SWITCHES & SOCKETS (Socket and Switch Types)
		LUMINARIES (Luminary Types, Electrical Terminals, Cable Trays, Signal Lamps etc.)

Figure 10: Electrical works.

As shown in Figure 10, “Electrical Works” are grouped as wiring, fuse & panels, switches & sockets, and luminaries with the calculations of total purchased and total used materials. According to the data that is taken from the relevant company is that no wasted materials in this category during the construction process, too. According to the meetings and data records, all electrical works were finalized with the needed and calculated amount during the construction process. But it is thought that defining define waste amount should be so sensitive especially for cables. So, it is determined that it can be missing information about the company to have record about this material list in terms of not being standardized materials like cables. On the other hand, it is thought that the company utilizes such materials in other projects and therefore does not keep the data regularly because it does not consider them as waste.

PRODUCT BREAKDOWN STRUCTURE		
FITTINGS	SCREWS	SCREWS (Gutter Hang, Roof Rafter Screws, End Mills etc.)
	ANCHORS	DOWELS (Steel Dowels)
	OTHER	OTHER (Prefabricated Windows, Handles, Door Locks, Ropes, Silicones etc.)

Figure 11: Fittings.

The most waste is determined in the fittings category in this project (Figure 11). Because of not being standardized products/components but being so many pieces in this category, waste is occurred for this project. Although, these products/components were waste for this project, this project's waste was used in another project according to the meetings with the the authorized person(s).

Conclusion

The most important step is eliminating the waste first. So, figuring out the waste idea, regarding the value concept, is essential. Classifying the waste is another important issue to manage them well. Off-site production and standardization can help to minimize the products/components waste during the construction site. So, the designing process, production method selections gain importance.

In this study, the project, which is composed of 4 buildings, is evaluated in terms of construction process product waste considering standardized products/components. According to the data records which are taken from the relevant company, it is seen that products/components waste is not occurred in the standardized products/components which are off-site production. The result can reveal the efficiency of standardization during the implementation at the construction site.

Standardization is thought a powerful for waste management. It is believed that it should be cared during the design process considering the whole project life cycle. To effective waste management and minimizing/eliminating products/component waste, keeping site records in terms of waste management and organizing the design process with the awareness of waste management gain importance. New research could be conducted on how to designs could be improved for the construction projects using standardization for waste management without being a threat for the design creativity. On the other hand, new research could be conducted to investigate production process in terms of waste management.

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References

Aki, A., & Harri, H. (2014). The challenges of standardization of products and processes in construction. *Conference paper,* Norway.

Can, G., & Taş, E. F. (2022). Material wastes and management strategies in the building construction sites (BSC). *Proceedings of 7th International Project and Construction Management Conference* (pp. 1156-1168).

Council, G. D. (2018). *Draft waste management & minimisation plan.* Gisborne District Council.

Gibb, A. G. F. (2000). *Client's guide and tool kit for standardisation and pre-assembly*. Construction Industry Research and Information Association, London.

Gibb, A. G., & Isack, F. (2001). Client drivers for construction projects: implications for standardization. *Engineering, Construction and Architectural Management*, *8*(1), 46-58.

Koskela, L. (1992). Application of the new production philosophy to construction. *Stanford University, 72*, 39.

Imai, M. (2005). *Gemba Kaizen–management and quality improvement in the workplace*.

Insteel (2023). *Containers and prefabricated buildings*. https://insteel.com.tr/

Košturiak, J., Boledovič, Ľ., Kriťak, J., & Marek, M. (2010). *Kaizen, the proven of practice Czech and Slovak companies*.

Koskela, L. (2000). *An exploration towards a production theory and its application to construction*. VTT Technical Research Centre of Finland.

Li, H., Guo, H., Skibniewski, M. J., & Skitmore, M. (2008). Using the IKEA model and virtual prototyping technology to improve construction process management. *Construction Management and Economics*, *26*(9), 991-1000.

Mao, X., & Zhang, X. (2008). Construction process reengineering by integrating lean principles and computer simulation techniques. *Journal of Construction Engineering and Management*, *134*(5), 371-381.

O’Connor, R., & Swain, B. (2013). *Implementing lean in construction: lean tools and techniques-an introduction*. CIRIA, London.

Pasquire, C. L. & Gibb, A. G. F. (2002). Considerations for assessing the benefits of standardisation and pre-assembly in construction. *Journal of Financial Management of Property and Construction*, *7*(3), 151-161.

Tam, V. W., Tam, C. M., Zeng, S. X., & Ng, W. C. (2007). Towards adoption of prefabrication in construction. *Building and Environment, 42*(10), 3642-3654.

Womack, J. P., & Jones, D. T. (1996). Beyond Toyota: how to root out waste and pursue perfection. *Harvard Business Review, 74*(5), 140-151.

Womack, J. P., & Jones, D. T. (2003). *Yalın düşünce*. İstanbul Yalın Enstitüsü.

Investigation of the Effects of Indoor Thermal Comfort Conditions on Employees in Architectural Design Offices: Balikesir Case

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Abstract

Providing working environment conditions is one of the priority factors in terms of employee health and a healthy working environment. The physical characteristics of these spaces affect employees who spend most of the day in offices. The transparent/opaque surface ratio in the building envelope directly affects indoor thermal comfort. When the transparent/opaque surface ratio on the façade increases, and measures such as the use of sun shading elements are not taken, overheating problems arise during the cooling period and cause an increase in the cooling load. This may negatively affect the comfort of the users. As the amount of energy required to keep the air temperature in the office environment at the optimum level increases, user comfort is also negatively affected due to the decrease in temperature. This study will examine the effects of the facades of an office building used as an architectural design office in Balıkesir province on employee health. For this purpose, first of all, the factors affecting the user's comfort regarding the facade elements will be examined through mutual interviews. Then, the thermal simulation of the office was carried out in the Grasshopper/Ladybug program, and different variations in Balıkesir climate were evaluated.

Keywords: *working environmental conditions, thermal comfort, simulation, optimization employee health.*

Introduction

Within the scope of environmental sustainability, it is necessary to use energy efficiently and reduce the consumption of natural resources to leave a livable environment for future generations. Office spaces, where people spend most of their time, consume energy to provide indoor comfort conditions during the use phase of the building. Energy efficiency aims to use resources efficiently. In this context, the European Union (EU) took an important step in this regard by publishing the Building Energy Performance Directive (2002/31/EC) in 2002. With its revision in 2010, it was emphasized that the regulations should be prepared by considering the intended use of buildings. With the "Clean Energy" decisions taken in Europe in 2016, it is aimed to use energy efficiently by 32.5% in the European Union (EU) member states in 2030 (URL-1) (Union Oj of the EED). The Paris Agreement established by the European Commission targets a climate neutral economy by 2050 (Unluturk & Ugurlu, 2023). In addition, the EU operates EU Emissions Trading Schemes, which price greenhouse gas emissions to reduce emissions and create financial incentives for industry and businesses (Malinauskaite et al., 2019).

A large part of people's days are spent in offices, and according to a study conducted in 2006, about 48% of the natural gas consumed for heating in the world is used in offices. Commercial buildings and residences use 56% of the total electricity used in the world (Kalatas, 2009). Buildings have a significant impact on total energy consumption. For this reason, concepts such as "sustainable building", "energy-efficient building", and "low-energy building" have become popular (Su et al., 2021).

In addition to energy efficiency, indoor thermal comfort affects employee satisfaction and performance. Temperature perception may vary from person to person as it is affected by the climatic environment, heat resistance of clothing, body structure and personal characteristics. However, environmental factors and personal characteristics affect thermal comfort (Chen et al., 2003; İmancı, 2014). In addition, higher-than-optimum workplace temperatures increase the risk of accidents and reduce work efficiency (Kjellstrom et al., 2009; Krishnamurthy et al., 2017).

This study aims to optimize the u-value and shading elements of the window to ensure energy efficiency and employee comfort in an architectural office with a silicon glass façade. For this purpose, an office building with glass façade in Balıkesir in CSA climate type is considered. Firstly, the office user was interviewed about the thermal comfort of the office, and then a parametric model of this office was created in a Rhino/Grasshopper environment, and different suggestions were evaluated.

Motivation of Study

When the literature is examined, it is seen that there are many studies on indoor thermal comfort. In 2013, K. Fabbari studied a kindergarten in North Italy with 4 and 5-year-old students in his study on student satisfaction with thermal comfort in educational buildings. Fabbari made spot measurements with a datalogger in the kindergarten and also surveyed to investigate the children's satisfaction using the space. The results showed that comfort is important for children and that the PMV values they need are slightly higher than adults (Fabbari, 2013).

In 2021, Liu's study in China aimed to investigate the thermal performance of an educational building. A BIM-based model of the building was made in Revit, and energy consumption analysis was performed in DesignBuilder. As a result of the study, it was concluded that exterior walls and windows are the parameters that affect energy consumption the most (Liu et al., 2021). Darvish et al. used the monitoring and simulation method to study educational buildings with courtyards in Iran. As a field study, two courtyard buildings with and without trees on the campus of International Imam Khomeini University were taken as a case study. These buildings were monitored with a datalogger and modelled in the DesignBuilder program. The study is valuable in stating that vegetation reduces energy consumption (Darvish et al., 2021). Aboleta stated that the temperature to which buildings are exposed impacts cooling energy demand. In his 2021 study, buildings in Cairo were considered. This study states that vegetation in urban areas reduces the urban heat island effect (Aboleta, 2021).

Rawat, on the other hand, investigates the application of cool roofs in buildings in his study in 2022. It is stated in the literature that this practice reduces energy consumption in buildings and the Urban Heat Island effect. In the literature review, it was concluded that this roof is effective in energy saving and that this saving rate varies in different climate zones (Rawat, 2022). In 2022, Han et al. studied an office building in China. Within the scope of the study, the office building was monitored, and it was concluded that the building was 69% more energy efficient than the existing offices in China (Han et al., 2022).

One frequently applied method to optimize energy consumption and indoor thermal comfort is the optimization method. Su et al. created an optimization model to predict the thermal variables of buildings in two different regions in New Zealand during the year. As a result of the study, optimum models suitable for the climatic characteristics of different regions were obtained (Su et al., 2021). Motalebi et al. examined the existing structures and worked on improving them. The study used a BIM-based optimization method, and a 24% - 58.2% reduction in energy consumption was achieved in the scenario created (Motalebi et al., 2022).

The central hypothesis of this study is that the u-value and shading elements of the windows are practical for the optimum thermal comfort of a north-facing office space in a CSA climate type. In this context, an existing architectural office in Balıkesir is considered. In the study, first of all, interviews were conducted with office users in the working comfort of the space. Then, a parametric model of the office was created in the Rhino/Grasshopper environment, and window/wall ratio optimization was performed using the Octopus plugin.

Material and Method

Climate Data

The building with a silicon façade, which is the subject of the field study, is located in Balikesir. The location of Balikesir Province in Turkey is shown in Figure 1. Balikesir is in the CSA climate type, which is very dry and hot according to the Köppen Geiger climate classification. According to TS 825 climate classification, it is located in the 2nd-degree day zone of Turkey.

Figure 1: Location of Balikesir in Turkey.

According to data from 1937 to 2017, the minimum and maximum temperatures in Balikesir Province were 4.8°C in January and 24.8°C in July, respectively. The average temperature in Balikesir Province is 14.5°C, the highest temperature recorded so far is 43.7°C, and the lowest is -21.8°C (URL - 2). Figure 2 shows Balikesir temperature and wind data for 2019. The highest monthly average temperature occurs in July and August, at 29°C, and the lowest monthly average temperature in December and January is eight °C (Figure 2) (URL 3).

Figure 2: Balikesir Province 2019 temperature and wind speed values (URL 3).

Case Building

The study sample consists of an office building in the Karesi district of Balıkesir province. The field of activity of the office considered as a sample is architectural design. LED luminaires are used to illuminate the interior of the building, which is used as an architectural design office. In addition, daylight is mainly utilized from the front facade. This approach was taken into consideration in the interior workspace arrangement (Fig. 3).

Figure 3 shows the building's exterior image and floor plan where the architectural office subject to the field study is located. The architectural office is located on the fifth floor of the building and faces north, as seen on the floor plan. The examined office has one working area, one kitchen and one bathroom. The width of the office working area is 4.75 m., and the depth is 6.5 m. The working area of the office is actively heated with natural gas (combi boiler). The clean floor height of the office is 2.8 m. A black coloured silicon glass facade is used in the building.

Figure 3: Case building exterior and floor plan.

Method

In the study, the office user was interviewed first. A conversation was held about the impact of the office building façade on employee health and how building façades affect user comfort. A semi-structured interview method was used to interview the office user. The interview focused on the "impact of the office building façade on employee health" and "impact on user comfort". These two focal points include the office user's "satisfaction level with the heating and cooling of the office" and "the reflection of the operating costs of the office due to the amount of energy consumption for heating and cooling".

In the interview, it was concluded that the building faces north and is located on the last floor of the building, which negatively affects the heating of the space. The office user expressed the effect of the facades on employee health as "it increases the happiness of the employee because the interior space receives daylight all day long". He also mentioned the adverse effects of the façade with the statement that "due to the excessive amount of glass surface, the energy required for heating increases due to the high heat transfer during the winter months". In the office, users' opinions on working comfort, such as a "spacious indoor environment" and "positive psychological effects," are mentioned. Table 1 indicates the thermal comfort criteria.

Table 1. Criteria for thermal comfort.

Criteria	Score
Necessary measures have been taken to prevent overheating in the interior	1-5
Made thermal insulation applications	1-5
Use a heat recovery system	1-5
Measures taken to prevent air infiltration	1-5
Indoor temperature does not adversely affect working performance	1-5
The amount of energy required for cooling in summer is not very large	1-5
The amount of energy required for heating in winter is not very large	1-5

Then, a parametric model was created in the Rhino/Grasshopper interface to simulate the energy of the examined office. In Honeybee, a plugin of Grasshopper, the climate data of Balıkesir province were entered into the system. The model's energy simulation was performed using Energyplus and Openstudio programs. Then, to reduce the amount of energy consumed by the office for heating and cooling, the u-value of the office windows and the solar shading element properties (number and reflectivity) were changed. The simulations were performed again, and the results were compared (Figure 4).

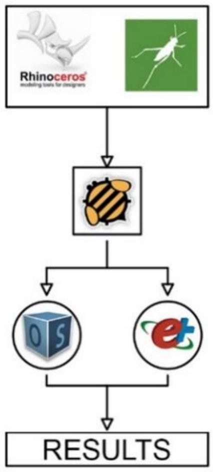

Figure 4: Workflow.

Energy simulation: Construction sets are created in Honeybee. Since the office user is a single person, it is specified as one person. Activities in the office and the frequency of use of electrical devices are also included in the model. Sitting and using computers occur in the office. There are four 32-watt LED bulbs in the office. The third stage of the work is to integrate the 3D model in the Rhino interface into Honeybee.

Space heating is also entered into the model as natural gas (combi boiler). Additionally, when the temperature of the space drops below 21 ◦C, the building starts to be heated, and when this temperature rises above 24 ◦C, it is cooled [40]. In the last stage, Balikesir province climate data is processed into the model and simulation is performed.

Results

The criteria specified in Table 1 were evaluated in the interview with the office user. In the evaluation, 5 points were given if the office space meets the specified criteria in the best way and 1 point if it does not. Table 2 shows the user evaluation obtained as a result of the interview. The table shows that the temperature in the office interior does not negatively affect the performance of the employees. This criterion received the highest score by the user. However, the building lacks heat recovery systems, one of the most significant deficiencies. This hurts energy efficiency.

Table 2. Evaluation of criteria for thermal comfort.

Criteria	Score
Necessary measures have been taken to prevent overheating in the interior	2
Made thermal insulation applications	2
Use a heat recovery system	1
Measures taken to prevent air infiltration	3
Indoor temperature does not adversely affect working performance	4
The amount of energy required for cooling in summer is not very large	3
The amount of energy required for heating in winter is not very large	2

Figure 5 shows the energy model prepared in the Rhino interface. First of all, the existing state of the office was modelled. There are no sun-shading elements in the existing state of the building. In addition, the transparent surface is designed as a silicon glass facade. Currently, the u value of the silicon glass facade is 1.6, and there are no shading elements. According to the data obtained at the end of the simulation, the average heating energy per m^2 is 117.11 kWh, while the average cooling energy per m^2 is 60.71 kWh annually.

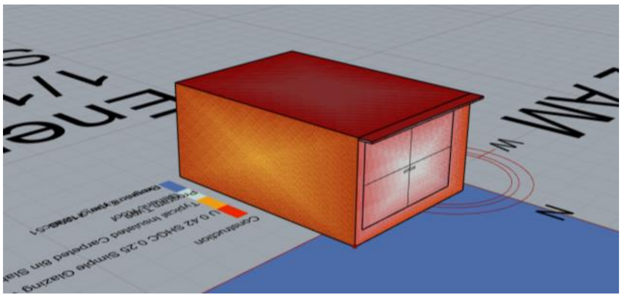

Figure 5: Rhino model.

Table 3 shows the cooling rates per m2 of the proposals. The proposals are similar. It is seen that the presence of shading elements during the cooling period reduces cooling energy consumption as it provides controlled entry of daylight into the indoor environment. Table 3 shows that when shading elements are not used, and the u value is 3.0, the proposal with 60.71 kWh consumption has the highest consumption. Table 53.10 shows the best results with a consumption of 53.10 kWh when the distance of the shading elements is 15 cm, and the u-value of the glass is 0.8.

Table 3. Cooling energy per m^2 of suggestions (kWh).

Distance of shading elements	U value		
	0.8	1.6	3.0
No shading elements	60.70	60.71	60.71
15 cm	53.10	53.12	53.13
30 cm	55.24	55.25	56.60

Table 4 shows the heating rates per m^2 of the suggestions. There is no significant difference between the suggestions. It can be seen that the presence of shading elements during the heating period increases the heating energy consumption as it reduces the entry of daylight into the indoor environment. Table 4 shows that when the spacing of the shading elements is 15 cm and the u value is 3.0, the proposal has the highest consumption with 119.95 kWh. The table shows that the proposal with no shading elements and a u value of 0.8 has the lowest energy consumption with 117.10 kWh energy consumption.

Table 4. Heating energy per m^2 of suggestions (kWh)

Distance of shading elements	U value		
	0.8	1.6	3.0
No shading elements	117.10	117.11	117.11
15 cm	119.90	119.95	119.95
30 cm	118.05	118.06	118.06

Discussion and Conclusions

In order to examine the effect of the façade of the office building, which was primarily considered as a field study in the study, on employee health and how building facades affect user comfort, an energy simulation was made by creating a parametric model in the Rhino/Grasshopper interface. Energy simulation of this model was carried out using Energyplus and Openstudio programs. Then, in order to reduce the amount of energy consumed by the office building in the interior, the simulations were carried out again by changing the u-value of the windows and the number and reflectivity of the sunshades, and the results were compared.

When the simulation results in the study are examined, using a shading element for cooling energy in the office building and its distance of 15 cm ensures the least consumption of the building. Although there is no significant difference between the values, the presence of the shading element is important. The low u value of glass is also among the factors that provide less consumption and better thermal insulation. For heating energy in the office building, not using shading elements and having a low u value provides the lowest energy consumption.

This study emphasizes the effect of indoor thermal comfort conditions on employees in energy efficient office building design. The transparent/opaque surface ratio in the building envelope and the use of shading elements directly affect the indoor thermal comfort. It provides information for future studies on how different materials to be used in the building envelope will affect interior comfort.

References

Aboleta, A., (2021). Reducing Outdoor Air Temperature, Improving Thermal Comfort, and Saving Buildings' Cooling Energy Demand in Arid Cities – Cool Paving Utilization, *Sustainable Cities and Society* 68(1):102762, 10.1016/j.scs.2021.102762.

Chen, M. L., Chen, C. J., Yeh, W. Y., Huang, J. W., & Mao, I. F. (2003). Heat stress evaluation and worker fatigue in a steel plant. *Aiha Journal,* 64(3), 352-359.

Darvish, A., Eghbali, G., & Eghbali, S. R. (2021). Tree-Configuration and Species Effects on the Indoor and Outdoor Thermal Condition and Energy Performance of Courtyard Building, *Urban Climate* 37(3):100861, 10.1016/j.uclim.2021.100861.

Fabbari, K., (2013). Thermal comfort evaluation in kindergarten: PMV and PPD measurement through datalogger and questionnaire, *Building and Environment* 68, 202-214, DOI: 10.1016/j.buildenv.2013.07.002.

Han, F., Liu, B., Wang, Y., Dermentzis, G., Cao, X., Zhao, L., Pfluger, R., Feist, W. (2022). Verifying of the feasibility and energy efficiency of the largest certified passive house office building in China: A three-year performance monitoring study, *Journal of Building Engineering* 32(7), https://doi.org/10.1177/1420326X231169874.

İmancı, C. (2014). *Döküm atölyelerinde termal konfor şartlarının incelenmesi*. İş Sağlığı ve Güvenliği Uzmanlık Tezi, TC Çalışma ve Sosyal Güvenlik Bakanlığı İş Sağlığı ve Güvenliği Genel Müdürlüğü, Ankara.

Kalatas, H. (2009). Leed Yeşil Bina Sertifikalandırma Programı. *XI. Ulusal Tesisat Mühendisliği Kongresi*, 1069-1078.

Kjellstrom, T., Holmer, I., & Lemke, B. (2009). Workplace heat stress, health and productivity– an increasing challenge for low and middle-income countries during climate change. *Global Health Action*, 2(1), 2047.

Kjellstrom, T., Lemke, B., & Otto, M. (2017). Climate conditions, workplace heat and occupational health in South-East Asia in the context of climate change. *WHO South-East Asia Journal of Public Health*, 6(2), 15-21.

Liu, Y., Chen, H., Zhang, L., Feng, Z., (2021). Enhancing Building Energy Efficiency Using a Random Forest Model: A Hybrid Prediction Approach, *Energy Reports* 7, 5003-5012. https://dx.doi.org/10.1016/j.egyr.2021.07.135

Malinauskaite, J., Jouhara, H., Ahmad, L., Milani, M., Montorsi, L., & Venturelli, M., (2019). Energy efficiency in industry: EU and national policies in Italy and the UK. *Energy* 172:255e69. https://doi.org/10.1016/j.energy.2019.01.130.

Motalebi, M., Rashidi, A., & Nasiri, M. M. (2022). Optimization and BIM-based lifecycle assesment integration for energy efficiency retrofit of buildings, *Journal of Building Engineering* 49, https://doi.org/10.1016/j.jobe.2022.104022

Rawat, M., & Singh, R. N. (2022). A study on the comparative review of cool roof thermal performance in various regions. *Energy and Built Environment*, 3(3), 327-347.

Su, Z., Wu, J., & Berti, S. (2021). Thermal Variables Estimation by a Metaheuristic-Based Method: Cases of New Zealand, *Energy Reports* 7, 5045-5058, https://doi.org/10.1016/j.egyr.2021.08.032 .

Ünlütürk, M. S., & Uğurlu, İ. (2023). Investigation of Energy Consumption at Different Floors in Buildings And Improvement Of Energy Efficiency: Balikesir Case. *Karesi Journal Of Architecture*, 2(2), 38-63.

URL 1: Commission E. COMMUNICATION from the commission clean energy for all Europeans. *EUR-Lex - 52016DC0860 - EN - EUR-Lex*; 2016. https://eur-lex. europa.eu/legal-content/en/TXT/?uri¼CELEX:52016DC0860. [Accessed 27 April 2020].

URL 2: *Balıkesir İlinin İklim Durumu*, 15 Ocak 2020, [Online], Erişim adresi: http://izmir.mgm.gov.tr/files/iklim/balikesir_iklim.pdf.

URL 3: *Balikesir Wheather Forecast*; 15 Ocak 2020, [Online], Erişim adresi: https://www.worldweatheronline.com/balikesir-weather/balikesir/tr.aspx.

Climate Change and Construction: Exploring the Intersection of Challenges and Solutions

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Abstract

Climate change represents one of the most formidable challenges of the contemporary era. Causing a wide spread impacts on the construction industry worldwide due to the increase of greenhouse gases (GHG) resulting in global warming and increase weather events. The study's aim is to understand how climate change impacts the construction industry and identify effective strategies for resilience. Employing a research methodology encompassing a survey, and targeted interviews with key stakeholders—including industry professional, and environmental specialist as well as literature review. The key results identified that (1) High temperatures, (2) Flooding and (3) cyclones are the most significant challenges facing Oman construction leading to cost overrun, delays and disruption of site respectively. The most important factors to mitigate climate change in construction were identified as (1) Insurance policies reflecting climate risks, (2) Development of climate adaptation plans and (3) Zoning laws to prevent building in high-risk areas. The implications of this research are significant. Firstly, it enhances the global understanding of the vulnerabilities and risks the construction industry faces due to climate change. Secondly, it supplies crucial information to stakeholders and policymakers, supporting the formulation of strategies and policies to improve the construction sector's resilience and sustainability amidst the changing climate.

Keywords: *climate change, construction industry, infrastructure durability, labor productivity, resilience strategies, sustainable practice.*

Introduction

Climate change is defined as the shift in climate patterns mainly caused by greenhouse gas emissions from natural systems and human activities (Fawzy et al., 2020). Climate change represents one of the most formidable challenges of the contemporary era. Greenhouse gases like water vapor, methane, and carbon dioxide retain some of the sun's heat, maintaining Earth's temperature at a level suitable for human life (Romm, 2022). Climate change is primarily caused by the increase in the natural rate of greenhouse gases, which act as a blanket. These gases trap heat in the atmosphere, raising global temperatures and causing more intense weather occurrences. However, it is also necessary to examine the function of natural variability in the climate system. This includes both externally induced and internal variability. As CO2 is the primary human-caused emission, at the dawn of the Industrial Revolution 250 years ago, atmospheric CO2 levels were about 280 parts per million (ppm). Since then, primarily due to human activities, CO_2 levels have risen significantly, now exceeding 400 ppm. Notably, most of this warming has occurred since 1970 (Romm, 2022).

Sixth Assessment Report (AR6) from the Intergovernmental Panel on Climate Change (IPCC, 2023) confirms that human activities are influencing weather and temperature extremes worldwide. Despite international efforts, such as the 2015 Paris Agreement aiming to cap the global temperature increase at 1.5 to 2 degrees Celsius this century, current climate action plans are falling short. As the latest information collected by researches and United Nations Framework Convention on Climate Change (UNFCC, 2023) indicates that "climate action plans remain insufficient to limit global temperature rise to 1.5 degrees Celsius and meet the goals of the Paris Agreement". To maintain global warming below two degrees, we must limit atmospheric CO_2 (equivalent) concentrations to about 450ppm by the year 2100 (Hurlimann et al., 2019). In 2018, the world experienced 315 cases of natural disasters, with storms, floods, wildfires, and droughts accounting for approximately 93% of the total weather-related disasters (Fawzy et al., 2020). In 2023, the U.S. witnessed 28 distinct weather and climate disasters, incurring costs of at least one billion dollars. This record number positions 2023 as the year with the most billion-dollar disasters ever recorded in a single calendar year (Adam, 2024).

On the other hand, Indonesia experienced a high frequency of disasters related to climate change between 1998 and 2018, with 80% of these disasters being attributed to flooding (39%), heavy wind/storm (26%), landslides (22%), and drought (8%) (Haryanto et al., 2020). As heat waves in Europe intensified, in 2019, the United Kingdom witnessed a record-breaking heat wave with a temperature of 38.7 °C. By 2100, many northern places are predicted to see temperatures above 30 degrees Celsius at least once a decade (Christidis et al., 2020). The sector is responsible for 6.4% of global GHG emissions from buildings alone, with an additional 12% from indirect emissions linked to energy and heat production for these structures (Hurlimann et al., 2019). On the other hand, Climate change threatens the industry by altering weather patterns, which impact building methods, materials, and site conditions and increase the risks of coastal erosion, flooding, sea-level rise, strong winds, and drought.

Furthermore, extreme temperatures, precipitation, and high winds are the most disruptive weather conditions on construction, costing billions of dollars in additional expenditures and lost income annually (Schuldt et al., 2021). It is experiencing a transformative shift to address the challenges posed by climate change. The aim of the study is to understand how climate change impacts the construction industry and identify effective strategies for resilience. The next chapters are arranged as follows, Challenges, intersections and opportunities, Methods used, Results and discussion, and conclusion.

Challenges, Intersections, and Opportunities

Globally, over the past years, an increasing frequency of extreme weather events has been observed, which naturally affects all sectors, including the building and construction sector. As (Matthew, 2023) discusses, the increasing frequency and severity of climate-related disasters have significant implications for construction projects. Affecting timelines and increasing costs, such as an increase in tropical cyclone activity, an escalation in the number of hot days and nights, an increase in recurrent heat waves, and an increase in instances of heavy rainfall (Rahman, 2018). The rise in sea level is another impact. In 2023, the global sea level increased to a new high since the beginning of satellite altimetry measurement in 1993 by 110mm (WMO, 2019). These phenomena result in many problems in construction projects and existing infrastructure as challenges to the industry, which require more knowledge and thus understanding to find appropriate solutions for all parties. As (Kalogeraki & Antoniou, 2022) found that the construction sector is most vulnerable to extreme weather events (EWEs).

Furthermore, the tendency of weather patterns to include frequent occurrences of heavy rains, floods, and storms can reveal instances of substandard construction that might otherwise have remained unnoticed. This exposure will likely increase claims and create additional challenges, such as schedule delays and cost overruns. Through literature review of articles globally, Table 1 summaries some of the direct impacts of climate change categories on construction industry worldwide.

Table 1. Overview of climate change challenges globally.

County	Specific Examples	challenges of events	REFERENCE
UK	Warmer and wetter winters warmer and dryer summers	Increase the decay hazard of exposed timber.	(Curling & Ormondroyd, 2020)
Australia	Heat, wind	Managing employee health and safety, maintain supply chain reliability, avoid project delays, and maximize profit.	(Hurlimann et al., 2019)
China	Extreme high temperatures	adopted power rationing measures, resulting in a significant decline in the output of construction steel enterprises, construction progress of construction enterprises had to be postponed;	(Guan-bing et al., 2023)
	Extreme rainfall, strong winds	Workers' injury on construction site Site disruption	
USA	- HURRICANE (Katrina) - storm surges during Hurricane Katrina	Numerous structures and structures under construction were destroyed or weakened. Hurricane Sandy resulted in $185 million in damage to the World Trade Center construction site.	(Pamidimukkala et al., 2020)
Turkey	High temperatures	health risks to workers, technical challenges for specific construction processes like concrete work,	(Oruc et al., 2024)
Nigeria	Flooding	Extensive flood damage, affecting water-sensitive building services, destruction of building components—significant increase in maintenance costs.	(Ew & Akujuru, 2019)

On the other hand, the workforce plays a crucial role in the successful completion of any project; therefore, the workers may be affected by various climate changes such as temperature changes, harsh weather, and rising sea levels (RSL) (see Table 2). According to (Karthick et al., 2023), the Bureau of Labour Statistics (BLS), 907 workers were killed due to exposure to environmental heat stress during the period 1992–2019. Climate change impacts on labour productivity and agriculture are projected to have the largest negative economic consequences, with damages from sea level rise growing most rapidly after the middle of the century (Dellink et al., 2019). It is essential to address the challenges they encounter due to changing climatic conditions.

Table 2. Impacts of climate conditions on the workforce.

Challenge	Description (Potential risks)	References
High temperatures	For every increase of 1°C above 28°C, workers' productivity may decline by as much as 57%. Elevated temperatures can result in reduced work pace, a higher incidence of errors, and a heightened risk of accidents on the job.	(Schuldt et al., 2021)
Wind	High wind speeds increase the risk of worker accidents, such as falling objectives	
Precipitation	Light rain and heavy snowfall significantly affect construction productivity, leading to reductions of up to 40% and work stoppages while also shifting workers' focus toward protecting the site and materials.	
Cold temperatures	Cold weather impacts the skin, muscles, and internal body systems, leading to a decrease in the strength and efficiency of workers.	

Climate change also intersects with construction by affecting the prices of the materials. Building materials are one of the most important factors affecting the project cost. For instance, extreme weather events can disrupt supply chains, leading to shortages and consequently driving up prices, like what happened in the U.S. after Katrina hit, (Hanemann, 2008), mentioned that In the USA after Katrina, the prices of some building products rose by 5% - 10%—leading to extend the project timeline regardless the increasing costs. More than 60% of construction material prices face a significant statistical increase in the aftermath of a disaster (Khodahemmati & Shahandashti, 2020). On the other hand, with the insurance adjustment to the higher risks of climate change, such as flooding, high temperatures, and extreme events, the insurance costs can increase. The insurance industry is the world's largest industry in terms of revenues, and insurers bear a large portion of weather-related risks, such as damage caused by floods and storms (Milne, 2004). The potential of global warming to increase vulnerability to weather extremes is especially relevant for the insurance sector (Botzen et al., 2010). However, a study of five out of ten of the largest liability insurers and three additional insurers in the Netherlands concludes that climate change is not regarded as a problematic issue. However, Insurance has always played a central role in the construction industry as an effective and probably the most popular risk management tool (Akinradewo et al., 2019). Moreover, scarcity of resources means increased demand for a limited resource due to poor supply. Therefore, the disaster may result in damage to resources such as wood and iron at the construction site. Also, extreme weather may cause serious damage to infrastructure, such as roads. This results in a disruption of movement, such as what happened in America as a result of Hurricane Katrina, where Oil shortages resulting from the hurricane are affecting commercial infrastructure developers who rely upon diesel-consuming cement mixers, cranes, and other heavy machinery more than residential builders. As (Wedawatta et al., 2011) highlight, extreme weather events can affect the availability of construction materials, requiring construction organizations to be prepared and enhance their resilience. He focuses on small- medium enterprises and their vulnerability to EWEs.

GCC Perspective

Meanwhile, the Gulf Corporation Council Countries (GCCC) countries are witnessing significant developments in all fields. This puts the construction sector under great pressure. In the United Arab Emirates, the impact of unusually heavy rains on April 16, 2024, led to severe damage to infrastructure such as roads and ports. As reported by the National Centre of Meteorology, this event marked the largest amount of rain in the past 75 years (Radifah, 2024). The city of Al Ain witnessed structural defects in homes due to heavy hailstones in March of the same year, highlighting the need for robust construction practices.

Similarly, Saudi Arabia experienced unprecedented rainfall in April 2021, increasing the frequency and intensity of flash floods, which had a significant impact on construction site access and materials—a phenomenon linked to climate change (Abdulkareem & Ellaboudy, 2021). The UAE faces significant risks due to its low elevation, with more than 85% of the population and 90% of the infrastructure located just a few meters above the current sea level. This makes the region particularly vulnerable to rising sea levels (Melville-Rea et al., 2021). Qatar, also a coastal nation, has a significant infrastructure and population concentrated in low-lying areas, making it susceptible to the impacts of sea level rise (Khan et al., 2023). Across the GCCC, high temperatures critically impact worker productivity. In Qatar, construction sites face health challenges such as heat stroke, kidney disease, anxiety, and depression due to the arid and semi-arid climate conditions (Karthick et al., 2023). In Kuwait, despite a policy banning midday work, there is a substantial increase in the risk of occupational injuries during the hot summer months, with injury reports peaking during June, July, and August (7.2, 7.6, and 9.4 reported injuries per day, respectively) (Alahmad et al., 2023). Bahrain also reports a drop in productivity during hotter quarters compared to cooler ones, illustrating the broader impact of high temperatures on the construction industry (Rabayah, 2020). The GCC region, including Kuwait, faces unique challenges from dust storms. The dust in these areas is significantly packed with salt, which causes considerable challenges for building activities, particularly when dealing with wet concrete.

In such situations, education plays a vital role across different communities, such as public, engineering, and industrial sectors, to increase awareness of the climate change issue and how it impacts different industries, in which global warming leads to a surge in extreme natural events. And then starts to create an immunity to this issue. It is recognized that education and training are important matters as they help to reach infrastructure durability; however, raising awareness among people in construction is a challenge. Education has an important role as an agent in creating awareness, training and mobilizing young people in the face of the challenges of climate change.

In the hand of opportunities, over time, construction methods and materials have undergone significant evolution from ancient stones and clay to modern bricks and beyond. The ongoing quest for innovation is driven by various factors, including the pressing need to address climate change. According to the World Green Building Council's definition, a green building "reduces or eliminates negative impacts—and can create positive impacts—on our climate and natural environment" (WGBC, 2024). Green buildings are a set of green materials and practices represented by sustainable and energy-saving buildings in addition to green water consumption. However, more robust studies are required to validate the real performance of green buildings via Post-occupancy Evaluation (POE) (Zuo & Zhao, 2014). Smart solutions and technology can help with climate change adaptation and resilience, however, the deployment of smart technology may result in certain possible trade-offs and rebound effects (Sharifi & Amir, 2023). In construction (Hwang & Lee, 2017) suggests to use smart wristbands for continues heart rate monitoring which can effectively reduce health and safety risks and improving productivity among the workers. On the other hand, Oman has a natural system to contain the CO2 emission, because of the Peridotite rocks that acts as Dr. Kelman said who is one of a relative handful of researchers around the world who are studying the idea, It acts like a giant battery containing a lot of chemical potential, if used correctly and at the lowest costs, this will be a gateway to absorbing carbon dioxide for hundreds of years (Fountain, 2018). It is noteworthy that the exploitation of this type of rock is still under study.

Method

The method used in this paper begins with a review of the literature on the impact of climate change on the construction industry around the world, as shown in Table 1. The effects varied due to the geographical distance and the diversity of the climate, as each region has a special climate. Then, a little deeper look was taken at the six Gulf Cooperation Council countries, and finally, the focus was on Oman. What was noted is the lack of references that specifically talk about the challenges facing external construction activities. After reviewing the literature, a survey was developed to understand how climate change affects construction and what are the challenges and opportunities regarding this phenomena. This survey targeted workers and experts who hold certificates, advanced diploma, bachelors, masters and doctoral degrees. After that, and for greater accuracy, a number of interviews were conducted with a construction company in addition to the Environment Agency and the General Directorate of Meteorology for a deeper understanding of the current conditions in Oman.

Results

Forty-three (43) responses in total were obtained from the questionnaire, which was distributed in different ways among different professionals in the industry. From the survey, 13 were consultants, 12 site engineers, 6 construction managers, 3 Architects and 9 from other positions in the industry. It is the same with (Alnuaimi et al., 2010), who cited more than 300 times and had 43 responses. The data were tested with reliability and result returned Cronbatch alpha of 0.800 which is considered as good (Pallent, 2015). Anova test, a parametric test which is used between two or more independent variables to check the differences between answers was conducted for the data based on Experience, Position and level of knowledge as appear in table (3). The results indicate that there is no significant difference between the respondents.

Table 3. SPSS parametric results.

NO	variable	Parametric Test	sig
1	Experience	Anova	**0.497**
2	Position	Anova	**0.500**
3	Level of knowledge	Anova	**0.541**

The normality test was obtained to check that the questionnaire was normality distributed. The result for (Kolmogorov-Smirnova and Shapiro-Wilk) has (0.000 and 0.001), indicating that non-parametric statistics is required to further checking. The Kruskal Wallis Test was used to determine the differences between the responses, and from table (4) it is clear that there is no significant differences on the basis of experience in the field, current position, and the level of knowledge about climate change impacts on the construction meaning that the respondents agreed that the climate change impacts the construction activities in Oman.

Table 4. SPSS non-parametric results.

No	variable	Non-Parametric Test	Asymp. Sig.
4	Experience	Kruskal Wallis Test	**0.492**
5	Position	Kruskal Wallis Test	**0.587**
6	Level of knowledge	Kruskal Wallis Test	**0.485**

Table 5. Climatic challenges facing Oman construction.

Descriptive Statistics		
	Mean	Std. Deviation
High temperatures	**3.3023**	**1.08089**
Flooding	**3.1860**	**1.23935**
Cyclones	**3.1395**	**1.33776**
Rising sea level	**2.8605**	**1.12507**
Drought	**2.5116**	**1.09918**
Valid N (listwise)		

Table 6. Implications of climatic challenges on Oman construction industry.

Descriptive Statistics		
	Mean	Std. Deviation
Cost overrun	**3.6744**	**1.08498**
Delays	**3.4186**	**1.19985**
Site disruption	**3.3488**	**1.17278**
Loss productivity	**3.3256**	**1.12802**
Costs heating cooling	**3.0698**	**1.16282**
Contractual claims	**2.8605**	**1.10370**
Valid N (listwise)		

The Table 5 shows the challenges faced by Oman's construction industry based on the most significant, which has the higher mean value, and it is clear that the high temperatures are identified as the most critical challenge. According to Al Badi (2024) from the Environmental Authority, According to National Contributions data, future climate changes are expected to contribute to heat waves, coastal erosion, and reduced fish production. In this regard, Al Tobi (2024) said that based on the last 30 years' data, it is clear that the temperatures increased, and even some stations across the country recorded a 1-degree increase, and they anticipated an increase. Also, Al-Asmi (2024), a construction company owner, noticed that Climate change has manifested itself in the appearance of surface cracks due to the intense heat and the presence of a significant difference in temperature between night and day. Flooding is the second significant challenge, thirdly, cyclones. Oman is prone to cyclonic storms and extreme weather events, which are likely to increase both in frequency and intensity due to climate change (Al Wardy et al., 2016). Strong storms usually hit Oman every 3 to 4 years (AlRuheili, 2022). However, Al Tobi (2024) from the Department of Meteorological Studies said that under the current situation, they do not anticipate an increase in the frequency but rather an increase in the severity. One of the famous cyclones that hit Oman was Gonu on June 1, 2007, which caused 50 deaths in total. The damaged areas cost around $4.2 billion, and a number of major cities were flooded, including the city of Al-Qurum. The last cyclone that hit Oman was Shaheen, which mainly affected the northern east of Oman, leading to a new record as the first cyclone hit these areas in 130 years (Ibrahim et al., 2022). These events pose risks to ongoing construction projects and existing infrastructure, leading to delays, increased costs, and potential structural failures. Shows the damage by Shaheen in the civilian areas, especially in Al-Kaboura. RSL, Al Ruheili and Boluwade (2021) indicated that “cyclone Kyarr contributed to coastal erosion along the coastal zone of Al Batinah, with an erosion rate of about 40 m/year between 2018 and 2019” and the average erosion rate of the Al Batinah coastal region between 2017 and 2020 was 9 meters per year, constituting 85% of the area. Coastal regions of Oman, where significant development is concentrated, are especially vulnerable to these changes. It increases the risk of coastal erosion and flooding, which can undermine the foundations of buildings and other structures. The increasing temperatures also pose health risks to construction workers, potentially leading to heat stress and reducing labour productivity. This necessitates adjustments in work practices, including scheduling work at cooler times of the day and providing adequate hydration and rest periods. Lastly drought, which is the less damaged challenge.

The implication of the challenges discussed in the previous section appears to be that cost overrun, and delays are significant effects, with mean values 3.6744 and 3.4186, respectively as in Table 6. Al Alawi (2020) shows that the critical path can increase by 3-38% based on three projects studied. Another study suggests that the implementation of the effects of hot and humid weather can increase the duration of the project by 1-5% (Al-Ajmi et al., n.a.). Followed by site disruption due to a variety climate conditions, such as strong wind and heavy rainfall.

Table 7. Factors to mitigate climate change in Oman construction industry.

Descriptive Statistics		
	Mean	Std. Deviation
Insurance policies climate risks	**3.6744**	**1.08498**
Development climate adaptation plans	**3.5349**	**1.03162**
Zoning laws prevent building high risk	**3.3721**	**1.13438**
Urban forest strategy	**3.3488**	**1.04389**
Incorporation climate change urban planning	**3.3023**	**1.08089**
Policies supporting renewable energy adoption	**3.2558**	**0.97817**
Tax incentives climate resilient practices	**2.9302**	**1.14216**

Valid N (listwise)		

From Table 7, Insurance Policies for Climate risks to mitigate climate risks: With a mean rating of 3.6744. The standard deviation of 1.08498 demonstrates that respondents agree on the necessity of Insurance as a form of protection against climate-related losses. The goal is to transfer the risk of financial loss from the policyholder to the insurer, thus providing a safety net that can help entities recover more quickly after a disruptive event. As outlined by (Lubken & Mauch, 2011), Insurance is considered a gradually important risk control method. However, Nobanee et al. (2022) pointed out that during a natural catastrophe, it becomes difficult to enforce a rule for all insurance arrangements to be implemented appropriately while also compensating investors. This suggests that individual investors should self-insure to protect themselves against environmental and climatic hazards. Development plans designed for climate adaptation are highly appreciated, with an average score of 3.5349. The comparatively low standard deviation of 1.03162 demonstrates widespread agreement on the importance of proactive preparation in responding to climate change. In this regard, the success adaptation plans should focus on three areas: policy and economy, science and learning, and legitimacy to achieve the main goals as Olazabal et al. (2017) defined. The third-ranked opportunity to adapt to climate change is to use Zoning laws to prevent building in high-risk areas, as in Table 7. The higher standard deviation of 1.13438 may indicate differing opinions on their effectiveness or implementation, which seems to be normal because of the diverse range of environments in Oman, which could vary by region or local context. Then, the urban forest strategy is important, especially in the heat island represented by cities.

Conclusion

The science of climate change started in 1856 with experiments by Eunice Newton Foote demonstrating the greenhouse effect of carbon dioxide therefore, the essential science of climate change was there in the late 1950s (Maslin, 2021). Recently, Dr. Al-Zaaq confirmed that climate change has been an ongoing phenomenon since the formation of the Earth, a fact that scientists have only recently understood. He pointed out that the Arab region is experiencing falling temperatures while Europe is facing rising temperatures (Nada, 2024). However, regardless of the causes and trends, the construction industry must deal with these climate shifts. In mitigation, building practices must evolve in harmony with nature rather than disrupting it.

The study focuses on Oman as a country of the Gulf Cooperation Council that shares religion, culture, place, and certainly climate. The results reveal that the five most significant challenges facing the construction industry in Oman due to climate change were identified. The study also highlights the most critical paths to mitigate and adapt to climate change risks. Such findings are invaluable to stakeholders and policymakers in Oman and the wider GCC region. It is recommended that construction companies and their supply chains integrate climate impact assessments into their project schedules and link meteorological data directly to construction planning.

Furthermore, policymakers are urged to enhance cooperation across Omani sectors and ultimately expand this cooperation throughout the GCC. This would lay the foundation for improving construction practices and updating building codes to better deal with climate-related risks. The study also emphasizes the importance of investigating how Artificial Intelligence

(AI) can help identify and develop resilience strategies against climate-related threats. This exploration can provide pivotal knowledge to help us adapt to our changing world.

References

Adam, B. S. (2024). *2023: A historic year of U.S. billion-dollar weather and climate disasters*. https://www.climate.gov/news-features/blogs/beyond-data/2023-historic-year-us-billion-dollar-weather-and-climate-disasters

Akinradewo, O., Aigbavboa, C., Ngwenya, L., Thwala, W., & Ncube, T. (2019). Efficiency of insurance as a risk management tool in South African construction projects. *Proceedings of the International Conference Organization, Technology and Management in Construction and 7th International Project Management Association Research Conference*.

Al Alawi, M. K. (2020). Modeling, ınvestigating, and quantification of the hot weather effects on construction projects in Oman. *The Journal of Engineering Research, 17*(2), 89-99.

Al Ruheili, A. M., & Boluwade, A. (2021). Quantifying coastal shoreline erosion due to climatic extremes using remote-sensed estimates from Sentinel-2A data. *Environmental processes, 8*(3), 1121-1140.

Al-Ajmi, M., Al Alawi, M., Al-Harthy, I., & Al, K. (n.a.). *Modelling temperature and relative humidity effects in construction project duration in Muscat*.

Alahmad, B., Al-Hemoud, A., Al-Bouwarthan, M., Khraishah, H., Kamel, M., Akrouf, Q., Wegman, D. H., Bernstein, A. S., & Koutrakis, P. (2023). Extreme heat and work injuries in Kuwait's hot summers. *Occupational and Environmental Medicine, 80*(6), 347-352.

Alnuaimi, A. S., Taha, R. A., Al Mohsin, M., & Al-Harthi, A. S. (2010). Causes, effects, benefits, and remedies of change orders on public construction projects in Oman. *Journal of Construction Engineering and Management, 136*(5), 615-622.

AlRuheili, A. M. (2022). A tale of Shaheen's Cyclone consequences in Al Khaboura City, Oman. *Water, 14*(3), 340.

Botzen, W., Van den Bergh, J., & Bouwer, L. (2010). Climate change and increased risk for the insurance sector: a global perspective and an assessment for the Netherlands. *Natural Hazards, 52*, 577-598.

Christidis, N., McCarthy, M., & Stott, P. A. (2020). The increasing likelihood of temperatures above 30 to 40 °C in the United Kingdom. *Nature Communications, 11*(1), 3093.

Curling, S. F., & Ormondroyd, G. A. (2020). Observed and projected changes in the climate based decay hazard of timber in the United Kingdom. *Scientific Reports, 10*(1), 16287.

Dellink, R., Lanzi, E., & Chateau, J. (2019). The sectoral and regional economic consequences of climate change to 2060. *Environmental and Resource Economics, 72*(2), 309-363.

Ew, D., & Akujuru, V. (2019). Impacts of flood on Ekeki Housing Estate Phase 2, Yenagoa, Bayelsa State, Nigeria. *International Journal of Scientific and Research Publications, 9*, 9491.

Fawzy, S., Osman, A. I., Doran, J., & Rooney, D. W. (2020). Strategies for mitigation of climate change: a review. *Environmental Chemistry Letters*, *18*(6), 2069-2094.

Guan-bing, M., Kai, X., & Kai-ling, D. (2023). Extreme climate risk and financial performance in the construction ındustry: empirical evidence from listed companies in China. *Journal of Risk Analysis & Crisis Response*, *13*(3), 185-198.

Haryanto, B., Lestari, F., & Nurlambang, T. (2020). Extreme events, disasters, and health impacts in Indonesia. In R. Akhtar (Ed.), *Extreme weather events and human health: ınternational case studies* (pp. 227-245). Springer International Publishing.

Hurlimann, A. C., Warren-Myers, G., & Browne, G. R. (2019). Is the Australian construction industry prepared for climate change? *Building and Environment, 153,* 128-137.

Hwang, S., & Lee, S. (2017). Wristband-type wearable health devices to measure construction workers' physical demands. *Automation in Construction, 83*, 330-340.

Ibrahim, O. R., Al-Amir, M., & Al-Maghawry, S. (2022). Tracking the damages of the Shaheen cyclone in the Sultanate of Oman. *Water Practice and Technology*, *17*(12), 2548-2553.

Kalogeraki, M., & Antoniou, F. (2022). Current research trends into the effect of climate change on civil engineering infrastructures: a bibliometric review. *IOP Conference Series: Earth and Environmental Science.*

Karthick, S., Kermanshachi, S., Pamidimukkala, A., & Namian, M. (2023). A review of construction workforce health challenges and strategies in extreme weather conditions. *International Journal of Occupational Safety and Ergonomics*, *29*(2), 773-784.

Khan, S. A., Al Rashid, A., & Koç, M. (2023). Adaptive response for climate change challenges for small and vulnerable coastal area (SVCA) countries: Qatar perspective. *International Journal of Disaster Risk Reduction, 96,* 103969.

Khodahemmati, N., & Shahandashti, M. (2020). Diagnosis and quantification of postdisaster construction material cost fluctuations. *Natural Hazards Review*, *21*(3), 04020019.

Lubken, U., & Mauch, C. (2011). Uncertain environments: natural hazards, risk and ınsurance in historical perspective. *Environment and History*, *17*(1), 1-12.

Maslin, M. (2021). *History of climate change*. Oxford University Press.

Melville-Rea, H., Eayrs, C., Anwahi, N., Burt, J. A., Holland, D., Samara, F., Paparella, F., Al Murshidi, A. H., Al-Shehhi, M. R., & Holland, D. M. (2021). A roadmap for policy-relevant sea-level rise research in the United Arab Emirates. *Frontiers in Marine Science, 8,* 670089.

Milne, J. (2004). Climate change, insurance and the building sector: synergisms, conflicts and adaptive capacity. *Building Research & Information*, *32*(1), 48-54.

Nobanee, H., Dilshad, M. N., Abu Lamdi, O., Ballool, B., Al Dhaheri, S., AlMheiri, N., Alyammahi, A., & Alhemeiri, S. S. (2022). Insurance for climate change and environmental risk: a bibliometric review. *International Journal of Climate Change Strategies and Management, 14*(5), 440-461.

Olazabal, M., Galarraga, I., Ford, J., Lesnikowski, A., & de Murieta, E. S. (2017). *Towards successful adaptation: a checklist for the development of climate change adaptation plans*. Basque Centre for Climate Change, Spain.

Oruc, S., Dikbas, H. A., Gumus, B., & Yucel, I. (2024). The ımpact of climate change on construction activity performance. *Buildings, 14*(2), 372.

Pamidimukkala, A., Kermanshachi, S., & Karthick, S. (2020). Impact of natural disasters on construction projects: strategies to prevent cost and schedule overruns in reconstruction projects. *Proceedings of Creative Construction e-Conference*.

Radifah, K. (2024). *Dubai floods: why UAE received the country's highest rainfall ın 75 years, and role of climate change.* https://news.abplive.com/science/dubai-floods-why-united-arab-emirates-received-highest-rainfall-in-75-years-and-role-of-climate-change-cloud-seeding-artificial-rain-abpp-1681028

Rahman, H. A. (2018). Climate change scenarios in Malaysia: engaging the public. *International Journal of Malay-Nusantara Studies, 1*(2), 55-77.

Romm, J. (2022). *Climate change : what everyone needs to know*. Oxford University Press.

Schuldt, S. J., Nicholson, M. R., Adams, Y. A., & Delorit, J. D. (2021). Weather-related construction delays in a changing climate: a systematic state-of-the-art review. *Sustainability, 13*(5), 2861.

Sharifi, A., & Amir, R., Khavarian, G. (2023). *Urban climate adaptation and mitigation*. Elsevier.

Wedawatta, G., Ingirige, B., Jones, K., & Proverbs, D. (2011). Extreme weather events and construction SMEs: vulnerability, impacts, and responses. *Structural Survey, 29*(2), 106-119.

Zuo, J., & Zhao, Z.-Y. (2014). Green building research–current status and future agenda: a review. *Renewable and Sustainable Energy Reviews, 30*, 271-281.

Green City Practices for Sustainable and Healthy Urban Spaces in Turkey: Examples of Sakarya Botanical Valley and Peynircioğlu Stream

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Abstract

Global problems such as climate change, environmental pollution, decrease in green areas and the transformation of cities into unhealthy living spaces are on the agenda of the world, and the green city concept was developed to prevent these problems. Green city practices are being implemented with various methods from micro to macro scale, including buildings, streets, neighborhoods, and cities. This study aims to examine the background and application of green city projects in Turkey to evaluate the effects of green city initiatives on urban life and sustainability. Green city practices implemented in Sakarya Botanical Valley and Peynircioğlu Stream were evaluated using the case study method under the subcategories of their effects on the city, citizens, nature, and sustainability. The contribution of the study to scientific and practical fields is to discuss the relationship of the green city concept, which is an important initiative to sustainable and healthy cities, with urban development and its importance for ecology and the natural environment. It is expected that the inferences obtained from the two case studies will guide the implementation of green city practices at different scales and in different regions.

Keywords: *green city, sustainability, Turkey, urban space.*

Introduction

In recent decades, various concepts and practices have been developed to prevent the negative effects of urbanization and the population living in cities on the environment and ecosystem. The green city concept as one of these concepts aims to create greener, healthier, livable, and sustainable cities by reducing the negative effects of climate change, air and environmental pollution, and consumption of natural resources with green projects (Aydın, 2021; Brilhante & Klaas, 2018). Projects such as using renewable energy resources, ensuring waste management, supporting the use of bicycles and electric vehicles, green roof and facade designs in buildings, parks and urban forests, and vertical farming applications not only support the green city initiative, but also positively affect human psychology, health, and quality of life (Aydın, 2021).

In the literature, the concept of green city has been discussed together with different concepts that evaluate current global problems and the effects of urbanization through case studies and offer suggestions. Researchers examine green infrastructure planning (Young, 2011), the impact of industrial production and recycling in cities on green city strategies (Ferrer et al., 2012), the impact of a green settlement designed as an eco-city on sustainable urban development (Freytag et al., 2014), the green city performance in fifty cities around the world (Brilhante & Klaas, 2018), the green city circle concept proposed to ensure resilience and energy efficiency in cities (Murielle Boulanger & Marcatili, 2018), the smart compact green city concept combining smart applications and green city strategies in compact cities (Artman et al., 2019), cities selected as European Green Capitals between 2010-2020 and green city indicators (Irmak & Avcı, 2019), green city branding (Wang, 2019), barriers to green city development (Debrah et al., 2022), and the green urbanization process in İzmir (Bilgen Kocatürk et al., 2023). However, there are not enough studies in Turkey that evaluate green city initiatives through cases whose results can be observed in terms of their background and implementation. This study aims to examine the background and implementation of green city projects in Turkey to evaluate the effects of green city initiatives on urban life and sustainability. For this purpose, green city projects implemented in Sakarya Botanical Valley and Peynircioğlu Stream were chosen primarily due to their compliance with the standards established by The International Association of Horticultural Producers (AIPH), the organization that has been organizing the World Green City Awards since 2022. These awards highlight global green infrastructure, sustainable practices, and the relationship between humans and environment (AIPH, 2024a). The inferences from both case studies are expected to guide the implementation of green city initiatives in different cities and at different scales.

Background Information

AIPH’s Green City Studies: Initiatives and Practices

International Association of Horticultural Producers (AIPH) established in 1948 by national plant producers. Today, it carries out important social and scientific studies and is responsible for organizing International Horticultural Exhibitions. The main objectives of AIPH (2024a) are to revitalize and maintain the permanent relationship between people and plants, which is fundamental to human health and well-being, to emphasize the roles of plants in ecosystem balance, to meet the needs of plant producers, to benefit from science and share new research, and to reveal the value of plants in an increasingly dense urban space. Currently, the AIPH community has 33 member states, supports, and encourages the work of its members to establish a healthy and stable balance between the human-technology-nature relationship.

AIPH (2024a) has introduced the “Green City” initiative to emphasize the importance of plants in urban areas, arguing that the problems occurring in the natural and built environment, ecosystem, people’s well-being, social harmony and economic structures will be improved with intelligently designed green areas. Green City initiative aims to create healthy and livable urban spaces for people, as well as to develop international standards for cities, make cities the focus of best practices, and increase awareness and expertise levels in societies (AIPH, 2024b). For this reason, news, guidelines and briefings about green city practices are shared to inform the public and experts and share information in order to ensure the integration of nature into the built environment on a global scale, green city articles are published in FloraCulture International magazine, conferences, “Living Green, Livable Cities” research symposium, “AIPH Global Green City Forum”, “AIPH Green City Case Study Collection” and “AIPH World Green City Awards” are organized (AIPH, 2024b). These studies emphasize the importance of sustainability principles and practices and aim to contribute to the United Nations

Sustainable Development's goals of good health and well-being, education, clean water and sanitation, sustainable cities and communities, climate action and life on land (AIPH, 2020).

The "Green City Guide" published by AIPH (2020) is an international initiative that aims to provide managers and experts responsible for applications in cities with the information they need to demonstrate the benefits of urban green space and green infrastructure. According to this guide, green city practices are examined at four scales: green cities, green neighborhoods, green streets and green buildings. "Case Study Collection" is published to share case studies that effectively implement green city principles. In the Case Study Collection, the design and implementation stages of successful projects, the reasons for their success, the project's contributions to nature and people, sustainability decisions and applications are discussed. Many countries participated in the AIPH World Green City Awards Collection in 2022 with different projects (Figure 1). From Turkey, Sakarya and İzmir cities participated with Sakarya Botanical Valley project and Peynircioğlu Stream Ecological Restoration Project. Sakarya Botanical Valley took part as a participant in the "biodiversity" and "health and wellbeing" categories, and Peynircioğlu Stream Ecological Restoration Project took part as a participant in the "climate change", "health and wellbeing" categories and received the "Highly Commended" award in the "climate change" category (AIPH, 2022a).

Figure 1: Countries participating in the World Green City Awards in 2022 (AIPH, 2022a).

Research Methodology

In this study, case analysis as one of the qualitative research methods was used. Case analysis is a systematic study in which the researcher examines in depth data on various variables on an individual, group, situation or place (Heale & Twycross, 2018). According to Johansson (2007), the case analysis method can be used frequently in social sciences, as well as in applied sciences such as architecture, planning, environmental studies, education, and business. Especially in practice-oriented areas of expertise such as architecture and planning, having knowledge of different case studies has an important place in terms of contributing to personal and professional experience. The logic of the sample determined in case analysis is different from statistical sampling (Meyer, 2001). Generalizations made from cases analyzed for a specific purpose are not statistical, but analytical and based on logic (Johansson, 2007; Widdowson, 2011). The scope of this study consists of the Sakarya Botanical Valley project and the Peynircioğlu Stream Ecological Restoration Project, organized for the purpose of green city initiative in Turkey. The reason for choosing these projects is that they are the first green city projects evaluated by AIPH in Turkey. The effects of the two projects on urban life and sustainability were evaluated within the scope of the subcategories determined by AIPH. Additionally, comparing the results of different but similar cases allows identifying specific variables that affect the differences (Widdowson, 2011). In this way, it is aimed to guide green city initiatives in Turkey and other developing countries as a result of the information and inferences obtained from the two case studies.

Evaluation of Green City Practices

Case 1: Sakarya Botanical Valley

AIPH Green City Awards Competition held for the first time in 2022. The city of Sakarya participated in the competition with the Sakarya Botanical Valley project and was evaluated in the “biodiversity” and “health and wellbeing” categories (AIPH 2022a). The location of the project is within the borders of Sakarya province of the Melen Transmission Line, which provides drinking and domestic water to İstanbul. Below, the effects of the project on urban life and sustainability within the scope of the green city initiative are summarized (AIPH, 2022b).

- *Addressing the urban challenge:* Various medicinal and aromatic plants were planted on the land, a large green area was created, and a natural living environment was provided for many creatures, especially bees (Figure 2). To prevent the negative effects of climate change, a healthier urban space has been created with the natural habitat of plants and bees. This project is also important in terms of raising public awareness about the natural environment, biodiversity, and health.
- *The power of plants and natural ecosystem to deliver benefits:* Botanical Valley aims to produce medicinal and aromatic plants used in different sectors such as medicine, food, chemistry, cosmetics, paint, to support beekeeping, and to contribute to the regional economy through production. In addition to increasing green areas and supporting biodiversity, it is aimed to develop the botanical valley as a recreation area, make it available to the public and create nature-tourism in the region.
- *Innovative and collaborative solution:* The project area was obtained as a result of expropriation work, and the local people supported the development of the botanical valley due to the socio-economic effects of the project. The green initiative developed by Sakarya Metropolitan Municipality is carried out with various experts under the main headings of plant production, beekeeping, and recreation area.
- *Implementation, impact and replicability:* In the Botanical Valley, natural products (oil, tea, soap, cologne, etc.) produced from aromatic plants such as rosehip, lavender, rosemary, sage, blackberry, valerian and linden are offered for sale at “Healing House”. Also, products provide income to locals. In this sense, each city can ensure the dissemination and sale of natural products and create greener cities by producing plant-based products suitable for its own climate and growing conditions.
- *Sustainability and resilience:* With the plants produced in the 60-kilometer area within the valley and the increasing bee population, the green area has been increased and the carbon footprint is aimed to be reduced. To prevent water waste, plants are watered using drip irrigation and no pesticides are used in production.
- *Monitoring, maintenance and management:* The cultivation of medicinal and aromatic plants and beekeeping are carried out with a contracted production model provided by the local people, and the control and development of the project is carried out under the management of Sakarya Municipality. Following the green infrastructure arrangement of the Botanical Valley, the Municipality continues to develop the area by preparing a social facility project that includes a collection garden, greenhouse, social facility,

recreation area, walking paths, camellias, cafeteria, and parking lot in order to offer nature-tourism to local and foreign visitors (Sakarya Municipality, 2022).

(a) (b)

Figure 2: a) Sakarya Botanical Valley project area; b) Aromatic herb field (AIPH, 2022b).

Case 2: Peynircioğlu Stream Ecological Restoration Project

İzmir participated in the AIPH Green City Awards Competition with the Peynircioğlu Stream Ecological Restoration Project. The project, which was evaluated in the "climate change" and "health and wellbeing" categories, won the "Highly Commended" award in the "climate change" category (AIPH, 2022a). Since 91% of the 4.4 million population living in the city lives in urban areas, problems such as air pollution, heat island effect, heavy traffic and loss of natural areas are experienced in the city (AIPH, 2022c). The location of the project is in Mavişehir District, at the starting point of the Gediz River Delta, which struggles with pollution as well as biodiversity and natural habitats. Below, the effects of the project on urban life and sustainability within the scope of the green city initiative are summarized (AIPH, 2022c).

- *Addressing the urban challenge:* The ecological restoration project was developed within the scope of nature-based solutions (NBS) developed to cope with biodiversity loss, heat waves and temperature increases, floods and the increase in CO^2 and other pollutants in the atmosphere. The ecological park is a part of the İzmir Living Park Project, which aims to protect green areas in the rural areas and natural areas of the city and combine them with the ecological corridor. This project aims to create urban parks where residents and tourists can enjoy the natural environment, along with ensuring ecological protection, agricultural production, and recreational use.
- *The power of plants and natural ecosystem to deliver benefits:* In line with NBS, restoration work was carried out on the 1.6-kilometer-long stream bed with permeable bicycle and pedestrian paths, green and permeable stream surface, green pavement applications, green fences, fruit walls and pollinator houses to prevent floods (Figure 3). These interventions have contributed to reducing air pollution, mixing rainwater with groundwater, regulating the microclimate, protecting biodiversity, and providing quality green and recreation areas to urban residents.
- *Innovative and collaborative solution:* This project is important that it sheds light on the problems of the future and inspires cities that support the natural life cycle by producing sustainable solutions. The project, developed by İzmir Municipality with local universities, SMEs and experts, is supported by the HORIZON 2020 URBAN GreenUP Project within the scope of the European Union Urban Planning Restructuring goals.
- *Implementation, impact and replicability:* In order to evaluate the effects of the project on nature and the environment, 2-year monitoring process was carried out by measuring baseline values before and after the project. According to the results obtained from the

monitoring process, a significant decrease in the amount of carbon and the heat island effect was detected, and the rainwater permeability capacity was increased. The project pioneered "İzmir's Strategy for Living in Harmony with Nature". İzmir representatives organize workshops to share experiences, develop urban plans and implement green initiatives with follower cities that want to develop NBS strategies.

- *Sustainability and resilience:* The implementation of NBS in Peynircioğlu Stream has provided a sustainable and adaptable green infrastructure by reducing the carbon footprint. The negative effects of intense urbanization on climate change and the natural environment have been controlled through urban revitalization, water intervention, green infrastructure strategies, use of recyclable and natural materials and non-technical interventions.
- *Monitoring, maintenance and management:* In line with resilience, sustainability and nature-friendly approaches, 1200 trees and 30.000 carbon sequestering plants were included in the area according to their adaptation and effectiveness features. Protection and maintenance work of the plants are carried out by İzmir Municipality. Also, efforts to meet the short and long-term needs of the region and green infrastructure continue.


(a)


(b)

Figure 3: a) Peynircioğlu Stream project area; b) Cycle and pedestrian roads (AIPH, 2022c).

Discussion and Conclusion

Global problems such as the continuing increase in the population living in cities, the gradual decrease in natural resources and biodiversity, pollution, climate change and increasing temperatures have caused green city strategies and practices to come to the fore in local and global agendas. In this research, the effects of two projects participating in the AIPH Green City Awards Competition from Turkey on urban space, life and sustainability were evaluated under six subcategories determined by AIPH. The research results and inferences obtained from the evaluation of two projects for cities planning to develop their green infrastructure and implement green city practices are as follows:

- *Addressing the urban challenge:* As implemented in Peynircioğlu Stream and Sakarya Botanical Valley, preserving flora, fauna and biodiversity supports the maintenance of the natural environment and provides a healthy and livable urban space (Aydın, 2021). In cities, there are settlements (Freytag et al., 2014), urban forests (Young, 2011) and urban recreation areas designed for green initiatives. Yet, there is a need to develop holistic green strategies spread throughout the city, such as İzmir Living Park Project, rather than a single project in cities.
- *The power of plants and natural ecosystem to deliver benefits:* As in Peynircioğlu Stream project, NBS can be used to prevent social and environmental problems in cities

(Kaçmaz, 2021). In addition, beekeeping and sales of aromatic plant products in the Botanical Valley protect biological diversity, support the natural ecosystem, and provide socio-economic contributions to urban residents.

- *Innovative and collaborative solution:* Carrying out green initiatives in cooperation with local government, public and experts and supporting them with international programs eliminates some barriers (Debrah et al., 2022), and increases the effectiveness of the project. Both projects in İzmir and Sakarya were carried out by the local municipality, and the project in İzmir was supported by an international program.
- *Implementation, impact and replicability:* Similar practices can be adapted or developed according to the climate and unique characteristics of cities. Experiences gained from the implemented applications can be used in other projects and shared with other cities.
- *Sustainability and resilience:* Climate change in cities and negative impacts on the natural environment can be prevented with NBS (Kaçmaz, 2021). As implemented in Peynircioğlu Stream project, developing green infrastructures with local, recycled, and natural materials contributes to sustainability (Ferrer et al., 2012).
- *Monitoring, maintenance and management:* Green practices can continue to be developed through short and long-term planning with the cooperation of local government, people and experts.

Although there are some initiatives implemented on project basis in Turkey and other developing countries, there is a lack of knowledge about the reason, content and methods of green city practices with a holistic approach covering the whole city. The importance of this study is to guide future projects by sharing the backgrounds and practices of two green city initiatives. The contribution of the study to literature and practice is that it invites the public, researchers, experts, local and central governments to cooperate in implementing green city practices by discussing the relationship of the green city concept, which is an important initiative for sustainable and healthy cities, with urban development and its importance in terms of ecology and natural environment. The limitation of this study is that it focuses on two green city projects in Turkey within the scope of the case analysis. It is crucial to plan future green city initiatives in a holistic and connected manner from macro to micro scale in cities. It is recommended to implement green initiatives with a holistic approach, with the participation and control of the public, experts, local and central governments in the planning, design, implementation, maintenance and repair processes to protect natural resources and ecosystem and to improve the quality of life of urban residents.

References

AIPH. (2020). *Green city guidelines.* https://aiph.org/green-city/guidelines-2020/

AIPH. (2022a). *Green city case studies collection*. https://aiph.org/green-city-case-studies/collection/

AIPH. (2022b). *Sakarya, Türkiye: Sakarya Botanical Valley*. https://aiph.org/green-city-case-studies/sakarya-turkiye-botanical-valley/

AIPH (2022c). *İzmir, Türkiye: Peynircioğlu stream ecological restoration project*. https://aiph.org/green-city-case-studies/izmir-turkiye/

AIPH. (2024a). *About*. https://aiph.org/about/

AIPH. (2024b). *Green city*. https://aiph.org/green-city/

Artmann, M., Kohler, M., Meinel, G., Gan, J., & Ioja, I. C. (2019). How smart growth and green infrastructure can mutually support each other—A conceptual framework for compact and green cities. *Ecological indicators*, *96*, 10-22.

Aydın, N. (2021). Yeşil şehirler. *Balkan ve Yakın Doğu Sosyal Bilimler Dergisi*, *07 (Special Issue)*, 116-124.

Bilgen Kocatürk, E., Özgören Şen, F., & Karabıyık Yerden, N. (2023). Yeşil şehir kavramı ve pazarlaması: İzmir'in yeşil şehirleşme sürecinin betimsel analizi. *Kent Akademisi*, *16*, 131-148.

Brilhante, O., & Klaas, J. (2018). Green city concept and a method to measure green city performance over time applied to fifty cities globally: Influence of GDP, population size and energy efficiency. *Sustainability*, *10*(6), 2031.

Debrah, C., Owusu-Manu, D. G., Kissi, E., Oduro-Ofori, E., & Edwards, D. J. (2022). Barriers to green cities development in developing countries: evidence from Ghana. *Smart and Sustainable Built Environment*, *11*(3), 438-453.

Ferrer, G., Cortezia, S., & Neumann, J. M. (2012). Green City: environmental and social responsibility in an industrial cluster. *Journal of Industrial Ecology*, *16*(1), 142-152.

Freytag, T., Gössling, S., & Mössner, S. (2014). Living the green city: Freiburg's Solarsiedlung between narratives and practices of sustainable urban development. *Local Environment*, *19*(6), 644-659.

Heale, R., & Twycross, A. (2018). What is a case study?. *Evid Based Nurs*, *21*(1), 7-8.

Irmak, M. A., & Avcı, B. (2019). Avrupa yeşil başkentlerin yeşil alan politikalarının incelenmesi. *Nevşehir Bilim ve Teknoloji Dergisi*, *8*, 1-19.

Johansson, R. (2007). On case study methodology. *Open House International*, *32*(3), 48-54.

Kaçmaz, G. (2021). İklim değişikliği ile mücadelede doğa temelli çözümler. *Peyzaj – Eğitim, Bilim, Kültür ve Sanat Dergisi*, *3*(2), 82-92.

Meyer, C. B. (2001). A case in case study methodology. *Field Methods*, *13*(4), 329-352.

Murielle Boulanger, S. O., & Marcatili, M. (2018). Metodologia circolare site-specific per la resilienza dei quartieri urbani: il Green City Circle. *TECHNE*, *15*, 203-211.

Sakarya Municipality. (2022). *Botanik Park için süreç başlıyor: Cennet vadisine harika bir tesis geliyor*. https://www.sakarya.bel.tr/tr/Haber/botanik-park-icin-surec-basliyor-cennet-vadisine-harika-bir-tesis-geliyor/20474

Wang, H. J. (2019). Green city branding: perceptions of multiple stakeholders. *Journal of Product & Brand Management*, *28*(3), 376-390.

Widdowson, M. (2011). Case study research methodology. *International Journal of Transactional Analysis Research*, *2*(1), 25-34.

Young, R. F. (2011). Planting the living city: Best practices in planning green infrastructure—Results from major U.S. cities. *Journal of the American Planning Association*, *77*(4), 368-381.

Barriers Encountered in Sustainable Building Projects and Their Relationships with Stakeholders

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Abstract

Today, concerns about increasing energy consumption and environment make the concept of sustainability widespread in building design. Stakeholders involved in these sustainable project processes face difficulties at some points. The aim of this study is to highlight the main barriers encountered in the sustainable building process. To achieve this, a comprehensive literature review was conducted, and 41 publications accessed through the Web of Science database were examined, using the words "sustainable + construction + barriers" in the title category. Among these publications, data obtained from those related to the subject were collected and the most encountered barriers were identified. These barriers were then linked to the stakeholders involved in project process. The scope of this study is limited to Web of Science database and selected keywords. The findings of this study are expected to serve as a guide to the future research on sustainable building projects within the construction industry.

Keywords: *barriers, construction industry, sustainability, sustainable building, stakeholder.*

Introduction

The construction sector plays a pivotal role in promoting sustainable economic development by attaining fundamental developmental objectives such as creating employment opportunities, generating income, and enhancing operational efficiency (Özustaoğlu & Ayalp, 2023). This sector, which has a great impact on human life, not only provides benefits to human life, but also causes various harms to the environment. Globally, buildings are responsible for approximately 40% of the world's total annual energy consumption (Ömer, 2008). This rate is a high rate in terms of energy consumption. The high rate of energy consumption of buildings has led to the use of the concept of sustainability in construction.

Sustainable construction project processes follow a different path than traditional project processes. In this case, stakeholders who are not experienced may face various difficulties. Previous studies have shown the importance of stakeholders involved in sustainable building projects being well-informed about the subject. To design in accordance with green building criteria, the project manager should ensure that project team members are involved at essential stages, in order to engage all project stakeholders and the main contractor in accepting the green building concept, and to accurately understand customer and stakeholder expectations (Kömürlü & Ceceloğlu, 2021). The complex structure of sustainable construction projects causes confusion for stakeholders involved in the process. In this case, stakeholders need to be informed about the process and act accordingly. The current literature indicates that all stakeholders should have a comprehensive understanding of the processes involved in sustainable building projects. To enable stakeholders in the sector to act successfully and professionally, variables should be considered from the outset (Akindele et al., 2023).

Unlike traditional projects, systems that will meet sustainability targets are included in the projects. Challenges are encountered in sustainable building construction processes due to the fact that it is a developing concept. Although there are several research on the barriers of sustainable construction projects, it has been observed that there are a limited number of studies that address these barriers from the perspective of stakeholders. This study aims to investigate the barriers encountered in sustainable construction projects by using the systematic literature method and to associate these barriers with the stakeholders involved in the process. Stakeholders considered within the scope of this study are designers, contractors, owners, project managers, employees and government.

Materials and Method

In this study, SLT (Systematic Literature Review) method was used. SLT is a secondary study that evaluates primary studies that contribute to the research topic; it is the review of the publications made to date on a determined subject with a predetermined method in order to find an answer to a research question (Jesson et al., 2011).

In this study, after determining the difficulties encountered in the management of sustainable building projects through a literature review, the relationships of these difficulties with the stakeholders involved in the project process were explained. Literature review was conducted by examining 41 publications published between 2019-2023, accessed through the Web of Science database using the words "sustainable + construction + barriers" in the title category. Among these, only 13 of the publications specifically address the barriers encountered in sustainable construction project. Therefore, the research was conducted based on these publications. Among these publications, those related to the subject were examined and the top 5 barriers identified by these publications were tabulated. Among the stakeholders involved in the project processes, the designer, contractor, owner, project manager, government, and employees were discussed.

Findings and Discussion

Sustainable construction projects follow a different process than traditional project processes. These projects have a complex structure and require expertise. The complexity of the projects and their areas requiring expertise create various barriers in the construction processes. In the examined publications, it is observed that barriers from different topics are discussed. Table 1 shows the most important 6 barriers revealed by these studies.

Table 1. Top 6 barriers encountered in sustainable construction projects.

BARRIER	STAKEHOLDER	AUTHORS
Difficulty in Finding Experienced and Expert Employees	• Designer • Contractor • Project Manager • Employees	• *Adel M. Ahmed, W. Sayed, A. Asran I. and Nosier Katar (2023)* • *Fitriani, H., & Ajayi, S. (2023)* • *Marsh, R. J., Brent, A. C., & De Kock, I. H. (2020)* • *Luo, M., Hwang, B.G., Deng, X., Zhang, N. and Chang, T. (2022)* • *Pham, H., Kim, S.Y. and Luu, T.V. (2020)* • *Tokbolat, S., Karaca, F., Durdyev, S., & Calay, R. K. (2020)* • *Omopariola, E. D., Olanrewaju, O. I., Albert, I., Oke, A. E., & Ibiyemi, S. B. (2022)*
Limited Knowledge and Lack of Awareness of the Clear Benefits of Sustainability Practices	• Designer • Owner • Contractor • Project Manager	• *Adel M. Ahmed, W. Sayed, A. Asran I. and Nosier Katar (2023)* • *Akindele, O. E., Ajayi, S., Toriola-Coker, L., Oyegoke, A. S., Alaka, H., & Zulu, S. L. (2023).* • *Fathalizadeh, A., Hosseini, M.R., Vaezzadeh, S.S., Edwards, D.J., Martek, I. and Shooshtarian, S. (2022)* • *Fitriani, H and Ajayi, S.O. (2023)* • *Omopariola, E.D., Olanrewaju, O.I., Albert, I., Oke, A.E. and Ibiyemi, S.B. (2022)* • *Osuizugbo C., Oyeyipo O., Lahanmi A., Morakinyo A. and Olaniyi O. (2020)* • *Tokbolat, S., Karaca, F.,Durdyev, S. and Calay, RK. (2020)*
Weak Government Support for Sustainable Construction	• Government	• *Akindele, O. E., Ajayi, S., Toriola-Coker, L., Oyegoke, A. S., Alaka, H., & Zulu, S. L. (2023).* • *Fathalizadeh, A., Hosseini, M.R., Vaezzadeh, S.S., Edwards, D.J., Martek, I. and Shooshtarian, S. (2022)* • *Luo, M., Hwang, B.G., Deng, X., Zhang, N. and Chang, T. (2022)* • *Pham, H., Kim, S.Y. and Luu, T.V. (2020)*

		• *Osuizugbo C., Oyeyipo O., Lahanmi A., Morakinyo A. and Olaniyi O. (2020)*
Lack of Relevant Laws and Regulations	• Government	• *Adel M. Ahmed, W. Sayed, A. Asran I. and Nosier Katar (2023)* • *Fathalizadeh, A., Hosseini, M.R., Vaezzadeh, S.S., Edwards, D.J., Martek, I. and Shooshtarian, S. (2022)* • *Luo, M., Hwang, B.G., Deng, X., Zhang, N. and Chang, T. (2022)* • *Osuizugbo C., Oyeyipo O., Lahanmi A., Morakinyo A. and Olaniyi O. (2020)*
Financial Restrictions / Economic and investment restrictions	• Owner • Designer • Contractor • Project Manager	• *Adel M. Ahmed, W. Sayed, A. Asran I. and Nosier Katar (2023)* • *Fitriani, H and Ajayi, S.O. (2023)* • *Kamranfar, S., Damirchi, F., Pourvaziri, M., Abdunabi Xalikovich, P., Mahmudkelayeh, S., Moezzi, R. and Vadiee, A. (2023)* • *Karji, A., Namian, M., & Tafazzoli, M. (2020)* • *Marsh, R., Brent, A.C. and Kock, I. (2020)* • *Osuizugbo C., Oyeyipo O., Lahanmi A., Morakinyo A. and Olaniyi O. (2020)* • *Omopariola, E.D., Olanrewaju, O.I., Albert, I., Oke, A.E. and Ibiyemi, S.B. (2022)* • *Tokbolat, S., Karaca, F.,Durdyev, S. and Calay, RK. (2020)*
Insufficient Collaboration Among Stakeholders	• Designer • Contractor • Project Manager • Employees • Owner	• *Fathalizadeh, A., Hosseini, M.R., Vaezzadeh, S.S., Edwards, D.J., Martek, I. and Shooshtarian, S. (2022)* • *Iqbal, M., Ma, J., Ahmad, N., Hussain, K., Usmani, M.S. and Ahmad, M. (2021)*

According to this table, the most frequently mentioned obstacle among the barriers mentioned by the authors in the examined works is "the difficulty in finding experienced and expert employees". Other most frequently cited barriers are "limited knowledge and lack of awareness about the clear benefits of sustainability practices", "weak government support for sustainable construction", "lack of relevant laws and regulations", "financial constraints".

Difficulty in Finding Experienced and Expert Employees: Since sustainable construction projects are still developing, it is difficult to find experienced employees in this field. This obstacle can be associated with the stakeholders involved in the project process: the contractor, designer, project manager and employees. The fact that these stakeholders have previously worked on sustainable construction projects or are knowledgeable on this subject will support the project in achieving its sustainability goals. In this context, stakeholders involved in sustainable construction projects need to stay up-to-date and follow innovations in their fields through continuous training and information sharing. In this way, it will be possible for the projects to be successful in terms of sustainability and to support the overall development in the sector.

Limited Knowledge and Lack of Awareness of the Clear Benefits of Sustainability Practices: This barrier may concern most of the project stakeholders. In cases where the designer, contractor, owner and project manager do not have knowledge about sustainable construction projects, they lack awareness about the benefits of sustainable construction projects. This may cause them to make wrong decisions by ignoring some situations when making a choice. Because the construction industry is client-driven, the degree to which clients are aware of, receive training in, and adopt sustainable construction practices is crucial to its implementation (Omopariola et al., 2022). Therefore, the level of awareness of the owner is important. From the designer's perspective, the designer may not have acquired much information about sustainable design during the education process. The contractor should also be knowledgeable about these issues. One should know how to use the materials and systems to be used in the construction process of sustainable projects, what to pay attention to, and act accordingly. If the project manager does not have knowledge about sustainability issues and lacks awareness, the project process cannot be managed smoothly. Project managers who are knowledgeable in sustainable construction projects will be able to direct the operation of the process correctly.

Weak Government Support for Sustainable Construction: This barrier is related to the government. Governments ought to regulate the sector through laws and regulations and use rewards and penalties to strike a balance between the interests of all parties involved (Pham et al., 2020). Government support is an important condition as a guide in sustainable construction projects. Supporting policies that would assist stakeholders in building sustainability capacity, particularly in the construction sector, should be given top priority by the government (Akındele et al., 2023). In the studies examined, it is observed that government support is insufficient. It is also evident that the lack of these practices causes difficulties in sustainable construction projects.

Lack of Relevant Laws and Regulations: This barrier is related to the government. Building codes and specific regulations must adapt to the growing trend of sustainable and green building practices (Adel et al., 2023). Laws and regulations that will ensure the success of sustainable construction projects should be developed and implemented. The development of these law and regulations will increase the implementation of sustainable projects.

Financial Restrictions: One of the important concepts in project processes is the concept of cost. In some cases, there are restrictions on cost. These restrictions cause delays in deciding on sustainable construction projects or failure to achieve the goals of the decided projects. This barrier is associated with the designer, contractor, owner and project manager. While it's a common misconception that sustainable buildings pay for themselves more quickly than conventional ones, clients may not realize this, which could work against them because the initial outlay may be a little higher (Fitriani & Ajayi, 2023). The financial constraints of the owner are effective in the decision-making phase of the project and the choices made during the project process. In this case, other stakeholders also act according to the financial constraints.

Insufficient Collaboration Among Stakeholders: Sustainable construction projects are projects that are complex and involve different stakeholders. Stakeholders involved in this complex process must establish healthy communication among themselves. They must cooperate when necessary and thus do not interrupt the functioning of the process. When there is an insufficient collaboration among stakeholders, sustainable projects struggle to succeed. Effective communication and coordination among project stakeholders, as well as open sharing of transparent project information, can facilitate the effective removal of this barrier (Iqbal et al., 2021).

In cases where the identified barriers cannot be overcome, projects have difficulty achieving their goals. In order for sustainable construction projects to be successful, barriers must be eliminated and the difficulties that may be experienced must be well understood and influence behavior. For this purpose, important barriers must be identified and necessary arrangements must be made to eliminate these barriers. These regulations should include situations such as increasing the laws and regulations made by the government or taking what is necessary to ensure proper cooperation between stakeholders.

Conclusion

There are barriers that stakeholders involved in sustainable construction projects face in the process. In order for projects to be successful, barriers must be emphasized, and stakeholders must understand these barriers and act with awareness.

In this study, research mentioning the barriers encountered in sustainable construction processes was examined through a literature review. The findings showed that the 6 most mentioned barriers are: (1) difficulty in finding experienced and expert workers, (2) weak government support for sustainable construction, (3) lack of relevant laws and regulations, (4) limited knowledge and lack of awareness of the clear benefits of sustainability practices, (5) financial restrictions, and (6) insufficient collaboration between stakeholders. To achieve success in sustainable construction projects, it's essential to actively identify and remove any potential barriers.

Unlike the studies on barriers in the literature, this study includes the most frequently mentioned barriers in relation to stakeholders. The difficulties identified in the study were explained and associated with the stakeholders involved in the project processes. The scope of this study is limited to Web of Science database and selected keywords. The findings of this research are expected to contribute to the construction industry by serving as a guide for stakeholders involved in sustainable construction projects.

References

Ahmed, A. M., Sayed, W., Asran, A., & Nosier, I. (2023). Identifying barriers to the implementation and development of sustainable construction. *International Journal of Construction Management*, *23*(8), 1277-1288.

Akindele, O. E., Ajayi, S., Toriola-Coker, L., Oyegoke, A. S., Alaka, H., & Zulu, S. L. (2023). Sustainable construction practice in Nigeria: Barriers and strategies for improvement. *Built Environment Project and Asset Management*, *13*(4), 590-609.

Brundtland, G. H. (1987). What is sustainable development. *Our Common Future, 8*(9).

Durdyev, S., & Ismail, S. (2016). On-site construction productivity in Malaysian infrastructure projects. *Structural Survey*, *34*(4/5), 446-462.

Fathalizadeh, A., Hosseini, M. R., Vaezzadeh, S. S., Edwards, D. J., Martek, I., & Shooshtarian, S. (2022). Barriers to sustainable construction project management: The case of Iran. *Smart and Sustainable Built Environment*, *11*(3), 717-739.

Fitriani, H., & Ajayi, S. (2023). Barriers to sustainable practices in the Indonesian construction industry. *Journal of Environmental Planning and Management*, *66*(10), 2028-2050.

Iqbal, M., Ma, J., Ahmad, N., Hussain, K., Usmani, M. S., & Ahmad, M. (2021). Sustainable construction through energy management practices in developing economies: An analysis of barriers in the construction sector. *Environmental Science and Pollution Research*, *28*, 34793-34823.

Kamranfar, S., Damirchi, F., Pourvaziri, M., Abdunabi Xalikovich, P., Mahmoudkelayeh, S., Moezzi, R., & Vadiee, A. (2023). A partial least squares structural equation modelling analysis of the primary barriers to sustainable construction in Iran. *Sustainability*, *15*(18), 13762.

Karji, A., Namian, M., & Tafazzoli, M. (2020). Identifying the key barriers to promote sustainable construction in the United States: A principal component analysis. *Sustainability*, *12*(12), 5088.

Kömürlü, R., & Ceceloğlu, D. (2021). Yeşil bina üretiminde proje yönetimi kapsamında yaşanılan zorluklar ve çözüm önerileri. *Artium*, *9*(2), 98-104.

Lima, L., Trindade, E., Alencar, L., Alencar, M., & Silva, L. (2021). Sustainability in the construction industry: A systematic review of the literature. *Journal of Cleaner Production*, *289*, 125730.

Luo, M., Hwang, B. G., Deng, X., Zhang, N., & Chang, T. (2022). Major barriers and best solutions to the adoption of ethics and compliance program in Chinese international construction companies: A sustainable development perspective. *Buildings*, *12*(3), 285.

Marsh, R. J., Brent, A. C., & De Kock, I. H. (2020). An integrative review of the potential barriers to and drivers of adopting and implementing sustainable construction in South Africa. *South African Journal of Industrial Engineering*, *31*(3), 24-35.

Omer, A. M. (2008). Energy, environment and sustainable development. *Renewable and Sustainable Energy Reviews*, *12*(9), 2265-2300**.**

Omopariola, E. D., Olanrewaju, O. I., Albert, I., Oke, A. E., & Ibiyemi, S. B. (2022). Sustainable construction in the Nigerian construction industry: Unsustainable practices, barriers and strategies. *Journal of Engineering, Design and Technology*.

Osuizugbo, I. C., Oyeyipo, O., Lahanmi, A., Morakinyo, A., & Olaniyi, O. (2020). Barriers to the adoption of sustainable construction. *European Journal of Sustainable Development*, *9*(2), 150-150.

Özustaoğlu, S., & Ayalp, G. G. (2023). Sürdürülebilir yapı üretim sürecinin önündeki engellerin belirlenmesi. *Mekansal Araştırmalar Dergisi*, *1*(1), 3-18.

Pham, H., Kim, S. Y., & Luu, T. V. (2020). Managerial perceptions on barriers to sustainable construction in developing countries: Vietnam case. *Environment, Development and Sustainability*, *22*, 2979-3003

Serpell, A., Kort, J., & Vera, S. (2013). Awareness, actions, drivers and barriers of sustainable construction in Chile. *Technological and Economic Development of Economy*, *19*(2), 272-288.

Tokbolat, S., Karaca, F., Durdyev, S., & Calay, R. K. (2020). Construction professionals' perspectives on drivers and barriers of sustainable construction. *Environment, Development and Sustainability*, *22*, 4361-4378.

Yılmaz, M., & Bakış, A. (2015). Sustainability in construction sector. *Procedia-Social and Behavioral Sciences*, *195*, 2253-2262.

World Energy Council (WEC) Turkish National Committee. (2008). Energy Management in the Building Sector.

Structural Rating System for Reliable Cities

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Abstract

Earthquakes that occurred in Turkey have resulted in damage to the existing building stock, reduced confidence in buildings, and raised questions about the building stock. This paper presents a structural rating system for reliable cities that can be used to assess the seismic performance of buildings. The system is designed to be used by engineers, architects, and other professionals involved in the design, as well as by building occupants who may not have technical knowledge. The rating system is easy to use and can be applied to buildings of all types and sizes. It provides a clear and concise assessment of a building's seismic performance and can be used to identify areas where improvements are needed. The rating system also includes a certification program that recognizes buildings that meet certain performance criteria. The certification program includes six levels: Bronze-I, Bronze-II, Silver, Gold, Platinum, and Diamond. Each level corresponds to a specific set of performance criteria that a building must meet to achieve certification. The certification program has led to contractors building more reliable structures. It is important to note that the certification levels need to be refreshed every 5 years by professionals to ensure that the buildings continue to meet the performance criteria. The structural rating system for reliable cities presented in this paper provides a valuable tool for assessing the seismic performance of buildings.

Keywords: *assessment, certification, rating system.*

Introduction

The earthquakes experienced in Turkey reveal that many existing structures are not resilient against seismic effects, raising awareness in society about the danger of earthquakes and the associated risks. This awareness primarily manifests itself in questions such as "Is the building we're in earthquake-resistant?" for those using the structure, or "Is this building sturdy?" for those considering renting or buying it. The inability to promptly answer these questions or rely solely on the words of the seller leads consumers to make uninformed decisions about renting or purchasing, as there is no alternative. However, unlike in the case of buildings, all users can access various test data, including durability tests for electronic devices like mobile phones or computers, before making a purchase and shape their decisions based on these test results and technical data. The necessity of informing society about buildings purchased at much higher costs and entrusted with personal safety has been realized.

This paper discusses the USRC and REDi studies conducted in the United States. Alongside this study, a certification system that can be understood immediately by the general public through certificates affixed to the entrances of buildings is presented. The awareness of risk in society will spread street by street with the certificate placed at the entrances of buildings. Although not a legal requirement, it is aimed for this practice to become a consumer demand over time and for contractors to change their standards and business practices to obtain this certification. With competing contractors marketing this certification and a rapid increase in the number of earthquake-resistant certified buildings in response to consumer expectations, an improvement of the building stock is expected.

The concept of a 'safe building' along with the certification system will not only benefit individual consumers and construction companies but also enable all institutions involved in emergency planning (such as identifying temporary shelter areas after earthquakes, determining potential open roads, etc.) to make more consistent plans. Additionally, the certification system will contribute to reducing structural risks in the long term, thus lowering post-earthquake repair costs, and bringing much more to the country than the potential additional costs of meeting certification requirements.

The Existing Rating Systems

The outcomes derived from assessing structures using various evaluation methods or mathematical models can only be comprehended and interpreted by individuals specialized in the field. Complexities arise in public comprehension due to terms like strength and displacement values, as well as collapse probabilities. To facilitate the easy presentation of structures' performance and resilience levels to the public, diverse rating systems have been developed. This paper will scrutinize the existing Redi (The Resilience-based Engineering Design Initiative) Rating System and the USRC (United States Resiliency Council) Rating System.

Both rating systems aim to prioritize "resilience-based design" in building construction. Resilience in building design denotes the capacity to revert to the initial state following an impact. Structural damage levels, the duration required for structural reusability, and probabilities of injury and loss of life are factors considered in structure ratings.

The Redi rating methodology is divided into three subcategories: earthquake, flood, and high winds. In this paper, only the earthquake subcategory will be addressed. Beyond linear elastic design or performance-based design, resilience-based design, primarily aims for the structure to be immediately ready for use after an earthquake. The Redi methodology has three different rating levels: Platinum, Gold, and Silver, with three different resilience categories and an operational loss estimation category. Resilience categories are divided into organizational resilience, structural resilience, and ambient resilience.

In the REDi methodology, the estimation of operational loss can be examined under two headings: direct financial loss estimation and operational loss duration estimation. For direct financial loss estimation, the PACT software allows for the application of the P-58 method in a digital environment, enabling the calculation of the repair cost ratio to the total structure value. This calculation does not include indirect costs such as costs arising from operational loss. In operational loss duration estimation, the REDi methodology identifies repair classes, factors delaying post-earthquake repairs based on past experiences, and predictions for post-earthquake regional electricity, water, and gas interruptions. Additionally, it presents a sequential method by incorporating delaying factors for determining return period, service loss duration, and full return period.

The Redi methodology initially employs the PACT software, which is based on the FEMA P-58 method, to determine average damage scenarios. Based on the resulting damage rates, each structural and non-structural element is assigned a repair class using the repair class tables provided in the Redi method. Factors influencing the attainment of the selected repair class for estimating operational loss duration are considered.

Identifying obstructive factors such as funding availability for initiating necessary repairs and contractor mobilization that affect the attainment of the determined repair class is essential, and these factors should be considered in the return calculation. Once these obstructive factors are addressed, building repairs are calculated on a floor-by-floor basis, considering all damaged elements. In the methodology, an evaluation is conducted by following a repair sequence between floors for the overall return period of the entire building.

The USRC Rating System, initiated by the United States Resiliency Council (USRC) in 2015, represents a significant advancement in the realm of public awareness and comprehension regarding building risk analysis outcomes. This innovative system was meticulously designed to offer a more transparent and straightforward depiction of the risks associated with various structures.

USRC presents its results using a 5-tiered star system, where the performance is directly proportional to the number of stars. Additionally, USRC offers two types of ratings: transaction rating and verified rating. Transaction rating is limited to a maximum of 3 stars for three separate criteria. Verified rating, on the other hand, is applied according to a 5-star system for each criterion.

The USRC methodology rates buildings based on the following criteria:
- according to the possible levels of injury and possible loss of life,
- according to the level of damage calculated by the ratio of the repair cost of the damage to the structure after the earthquake to the cost of rebuilding the building (Equation 1),
- according to the return period, which is the minimum repair period required for the people using the building to be able to re-enter and use the building after the earthquake.

R : Repair cost
RB : Reconstruction cost
D : Damage

$$\boldsymbol{D = R/RB} \tag{1}$$

According to the rating system, the available certifications include the Certificate, Silver Certificate, Gold Certificate, and Platinum Certificate. The minimum requirements for these certifications and the certification badges are summarized in Table 1 below.

Table 1. USRC methodology star system and certifications.

Certificate / Criteria	Safety	Damage	Recovery
Certificate	✮✮✮	✮✮	✮✮
Silver Certificate	✮✮✮	✮✮✮	✮✮✮
Gold Certificate	✮✮✮✮	✮✮✮✮	✮✮✮✮
Platinum Certificate	✮✮✮✮✮	✮✮✮✮✮	✮✮✮✮✮

The Proposed System for The Republic of Turkey

The existing assessment, rating, and certification systems worldwide face challenges in comprehensive utilization due to issues such as data uniqueness, material variations, and the variability of soil and seismic conditions, among others. Moreover, the scoring systems established by current systems lose their significance when applied outside their source countries and become merely useful for inter-structure prioritization. Additionally, due to the English-language nature of the resources associated with these systems and the fact that the native language of the country to be applied may not be English, there can be gaps and different interpretations in implementation. To overcome these challenges, there is a need for a document in the native language considering local soil conditions, historical earthquake data, seismic conditions, building types, and material varieties.

The proposed assessment, rating, and certification system in this study can be applied to both existing and future structures. The objective is to encourage construction and project firms to construct 'safe buildings' by implementing these conditions in new constructions. Furthermore, the establishment of a reliable organization for the inspection of buildings and testing of necessary conditions will lead to the employment of numerous engineers in this field.

The proposed system in the study consists of two stages: basic assessment and detailed assessment. Simple assessment can be utilized for quickly gaining insights about a structure and prioritizing specific facilities/neighborhoods/regions. Upon completion of the basic assessment, structures can obtain a bronze or silver certificate with 1, 2, or 3 stars on the six-star system. Table 2 provides all the criteria that need to be met for the star system after the basic assessment stages. Once the basic assessment is completed, structures that achieve a 3-star rating can proceed to the detailed assessment. The detailed assessment requires a meticulous approach considering both structural and non-structural elements of the building. The performance of the structure under earthquake conditions and the condition of the structure and its occupant's post-earthquake are calculated as a result of the detailed assessment. After the detailed assessment, structures can receive a certification of gold, platinum, or diamond on the certification system based on a six-star rating.

Table 2. Star and certification system based on basic rating.

Star	★ (Bronz Certificate)	★★ (Bronz Certificate)	★★★ (Silver Certificate)
Data	Complete Data	On-site observation* Complete Data	On-site observation* Complete Data
Modified FEMA P-154	Being above the Level-1 threshold value *	Being above the Level-1&2 threshold value *	Being above the Level-1&2 threshold value *
	P(Collapse) < 0.10	P(Collapse) < 0.06	P(Collapse) < 0.01
Modified HAZUS	Probable Loss < 0.30 P(Casualities)< %0.10 Recovery Duration ≤ 540d	Probable Loss < 0.25 P(Casualities)< %0.04 Recovery Duration ≤ 270d	Probable Loss < 0.20 P(Casualities)< %0.01 Recovery Duration ≤ 180d
Checklists	✓ (for 1-star)	✓ (for 2-star)	✓ (for 3-star)

*For existing buildings

The fulfillment of the simple assessment criteria shown in Table 2 enables the attainment of one, two, or three stars from the six-star system. As part of localizing the Hazus methodology, evaluating Turkey's past regulations and local conditions, has been updated as shown in Table 3.

- Pre-Code: Pre-regulation (no seismic calculation)
- Low-Code: Acceptance of low seismic forces
- Moderate-Code: Inadequate seismic calculation according to current regulations
- High-Code: Compliance with current regulations
- Special-High-Code: Design exceeding current regulations

Table 3. Localized Hazus methodology regulation selection table (Demir et al. 2023).

Seismic Hazard	**Pre 1968**	**1968-1975**	**1975-1999**	**1999-2018**	**Post 2018**
Very High PGA>0.60g	-	-	-	-	High-Code*
High 0.40g<PGA<0.60g	Pre-Code	Moderate-Code	Moderate-Code	High-Code	High-Code
Med-High 0.20g<PGA<0.40g	Pre-Code	Low-Code	Moderate-Code	Moderate-Code	Moderate-Code
Medium 0.10g<PGA<0.20g	Pre-Code	Pre-Code	Low-Code	Moderate-Code	Moderate-Code
Low PGA<0.10g	Pre-Code	Pre-Code	Pre-Code	Low-Code	Low-Code

**Special High-Code*

The localized Hazus methodology regulation selection table provided in Table 3 is prepared based on the Turkey Earthquake Hazard Maps (TDTH) for the scenario earthquake with a return period of 475 years (DD-2).

In order to proceed to the detailed assessment stage, the steps of the basic assessment must be completed, and the criteria for obtaining a silver certificate must be met. The relevant building, whether existing or to be newly constructed, undergoes a detailed assessment, which comprises six stages internally. These stages are provided sequentially as follows:

- Structural analysis (using the appropriate method described in the seismic code),
- Verification of the checklists,
- Generation of fragility curves,
- Calculation of performance (estimation of potential damage and loss),
- Determination of the number of stars based on the obtained results,
- Selection of the appropriate certification level.

After the completion of the basic assessment and the fulfillment of all criteria for the silver certification level, the detailed assessment stage commences with the use of checklists containing regulatory conditions. Different criteria levels are present in the checklists for the targeted star ratings, with a unique set for one and two-star ratings, and distinct ones for three, four, five, and six-star ratings.

The evaluation of structure performance is conducted based on analyses conducted using established three-dimensional mathematical models. The stages of generating fragility curves and calculating performance are completed as described in the FEMA P-58 methodology.

If, as a result of the detailed assessment, the structure fails to meet any of the conditions for a 4-star rating, it will be classified based on the 3-star rating determined by the basic assessment, and the certification process will be completed with a silver certificate. The detailed assessment rating criteria and appropriate certification levels are provided in Table 4. Fulfilling the detailed assessment criteria shown in Table 4 enables the attainment of four, five, or six stars from the six-star system.

Table 4. Star and certification system conditions after the DD-2 scenario earthquake, according to detailed assesment.

Star	★★★★ (Gold Certificate)	★★★★★ (Platinum Certificate)	★★★★★ (Diamond Certificate)
Basic Assesment (Silver)	✓	✓	✓
Calculated Performance	Probable Loss < 0.10 P(Collapse) < 0.005 P(Casualities)< %0.01 Recovery Duration ≤ 30d	Probable Loss < 0.05 P(Collapse) < 0.003 P(Casualities)< %0.003 Recovery Duration ≤ 3d	Probable Loss < 0.01 P(Collapse) < 0.001 P(Casualities)< %0.001 Recovery Duration ≤ 1d
Checklists	✓ (for 4-star)	✓ (for 5-star)	✓ (for 6-star)

In the proposed methodology of the study, the stars obtained from the simple and detailed assessments result in certification acquisition. Structures receiving one or two stars from the basic assessment are awarded a bronze certificate, while those rated with three stars qualify for a silver certificate. Structures obtaining four, five, or six stars from the detailed assessment respectively earn gold, platinum, or diamond certificates. Badges for the certifications are provided in Figure 1.

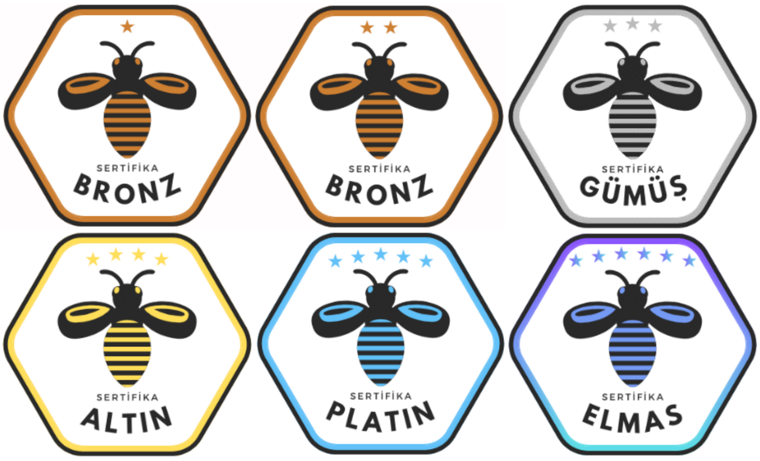

Figure 1: Badges of different certificate types.

Placing the acquired certificates at building entrances aims to provide occupants or prospective users with insights into the structure they are entering. Additionally, it is aimed to enable construction companies to utilize this as a marketing tool and to improve the design, construction, and inspection levels with the expectations of certificates that will emerge in the market. Targets expected under the influence of the DD-2 scenario earthquake from structures according to certificate levels are provided in Table 5.

At all certificate levels, no loss of life, regional collapse, or total collapse is expected. However, silver-certified buildings may experience damage to both structural and non-structural elements under the design earthquake effect. Damage or overturning may occur to objects in gold and silver-certified buildings; conversely, no damage or overturning is expected within diamond-certified buildings.

Table 5. Expected targets according to certification levels under the impact of DD-2 scenario earthquake.

Target / Certificate	**Basic Assesment**		**Detailed Assesment**		
	Bronz	**Silver**	**Gold**	**Platinum**	**Diamond**
Casuality	*Less Likely*	*Unexpected*	*No*	*No*	*No*
Collapse	*Less Likely*	*Unexpected*	*No*	*No*	*No*
Damage to Structural Elements	*Very Likely*	*Possible*	*Less Likely*	*Unexpected*	*No*
Damage to Non- Structural Elements	*Very Likely*	*Possible*	*Less Likely*	*Unexpected*	*Unexpected*
Injury Due to Falling Object	*Very Likely*	*Possible*	*Less Likely*	*Less Likely*	*Unexpected*
Damage to Valuable Objects	*Very Likely*	*Possible*	*Less Likely*	*Unexpected*	*Unexpected*
Injury Outside Structure	*Possible*	*Possible*	*Less Likely*	*Less Likely*	*Unexpected*
Probable Loss	*< %25*	*< %20*	*< %10*	*< %5*	*< %1*
Recovery Duration	$T > 180d$	$T \leq 180d$	$T \leq 30d$	$T \leq 3d$	$T \leq 1d$
Loss of Economic Value of the Building After the Earthquake	*Very Likely*	*Possible*	*Less Likely*	*Unexpected*	*No*

Certified structures must undergo on-site inspections every five years. Based on the approval of the on-site inspection team, the certificate can be renewed for a period of five years. This ensures that any potential structural and/or non-structural changes in the building are monitored, and in case of non-compliance, measures such as lowering the certificate level or revoking the certificate altogether can be taken. With this inspection mechanism, revocation of the certificate due to non-compliance will prevent any decrease in the value of the building or its components, thereby deterring any inappropriate structural or non-structural alterations in buildings.

Results

The study presents a two-stage assessment system consisting of 'basic assessment' and 'detailed assessment', each comprising six stars. Depending on the star rating, five different certification levels are established, namely bronze, silver, gold, platinum, and diamond. The validity and renewal criteria for the certificates issued to buildings are outlined within the study.

The aim of the star rating and certification presented in the study for Turkey is to enable individuals to gain insights about a building before renting/buying a flat or workplace, foster awareness among building occupants, and ensure earthquake awareness remains a continuous and high-quality topic in society. Additionally, it is intended to exert pressure on construction companies to meet certification requirements due to societal expectations, leading to a decrease in the value of uncertified buildings and encouraging property owners to support reconstruction efforts.

The basic and detailed assessments should be conducted by qualified individuals and companies, followed by oversight by the relevant authority. The rating and certification stages should be subject to institutional decision-making. Insurance companies, local governments, and the state should support this system and take necessary steps until market expectations are established.

In conclusion, this study aims to keep earthquake awareness on the agenda continuously and qualitatively, increase property owners' willingness during the building stock renewal process, exert pressure on construction companies through the certification system, contribute to the economy by reducing post-earthquake repair costs, and enhance the resilience of buildings and cities. In future studies, criteria and coefficients in the assessment stages can be improved based on experiments and experiences, and updates can be made in the rating and certification stages.

References

Almufti, I., & Wilford, M. (2014). *REDi rating system: Resilience-based earthquake design initiative for the next generation of buildings*. San Francisco, CA: Arup.

ASCE/SEI 41-13 *Earthquake performance rating system ASCE 41-13 Translation procedure*. (2017). Reston, VA: ASCE.

Demir, C. U., Peker, K., & Taskin B. (2023). *Hazus building capacity and pushover analysis curve comparison for concrete shear walls type structures built in Turkey in accordance with different seismic design level*. Istanbul, Turkey: Istanbul Technical University.

Federal Emergency Management Agency. (2015). *FEMA P-154: Rapid visual screening of buildings for potential seismic hazards: A handbook (3rd ed.).* Washington, DC: FEMA.

Federal Emergency Management Agency. (2015). *FEMA P-155: Rapid visual screening of buildings for potential seismic hazards: Supporting documentation (3rd ed.).* Washington, DC: FEMA.

Federal Emergency Management Agency. (2020). *Hazus earthquake model technical manual hazus 4.2 SP3*. Washington, DC: FEMA.

Federal Emergency Management Agency. (2018). *Seismic performance assessment of buildings volume I-methodology (2nd ed.).* Washington, DC: FEMA.

Türkiye Bina ve Deprem Yönetmeliği. (2018). [*Building and earthquake regulation of Turkey*]. Resmi Gazete, 30364, 18 Mart 2018.

United States Resilience Council (USRC). (2015). *United States resiliency council rating system implementation manual*.

A Research on Improving the Energy Performance of Residential Buildings

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Abstract

The research focuses on the improvement of lighting systems and the impact of photovoltaic applications on energy efficiency in buildings, aiming to increase building energy efficiency in response to global challenges such as population growth and urbanisation. The study, conducted in Antalya, located in the Mediterranean Climate Zone, evaluates the impact of upgrading the lighting system and integrating photovoltaic panels in three selected blocks within an island based settlements. Energy efficiency assessments cover a variety of factors such as building location, orientation and energy use scenarios including both natural gas and electricity for heating. Hourly analyses using DesignBuilder simulation and PVsyst software show that improving lighting leads to an average 6% reduction in energy consumption, while the implementation of photovoltaic systems leads to an additional 11% reduction. These findings underline the significant potential for reducing energy expenditure and environmental footprints. By demonstrating the effectiveness of an island-based strategy for improving building energy efficiency, this study extends the scope of energy saving initiatives from floors, spaces and buildings to an island-based approach.

Keywords: *building energy simulation, energy efficient design, energy efficiency, lighting system improvement, photovoltaic system design.*

Introduction

The rapid increase in the world population brings along the need for shelter. In order to meet this need, new settlement areas are opened, new buildings are constructed and cities are gradually growing. However, this rapid growth leads to an increase in energy demand. Scarce natural resources are consumed rapidly and unconsciously to meet this demand. This situation causes climate change and creates a global environmental disaster. As the demand for energy increases, energy costs also increase. This situation causes energy to become an important issue for countries.

Within the scope of the 2030 strategy, the European Union (EU) has set targets such as reducing greenhouse gas emissions by 40% compared to 1990 levels, increasing the share of renewable energy sources in energy consumption to at least 32% and achieving 32.5% energy savings (European Commission, 2014). In order to achieve these targets, according to the World Energy Outlook-2022 (WEO) Report of the International Energy Agency (IEA), 1.3 trillion dollars have been spent by the public and private sectors in the world for energy efficiency in buildings, industrial structures and transport. In addition, in order to reach the net zero emission target by 2050, the cost of clean energy investment in the world is projected to increase to approximately 4 trillion dollars by 2030 (IEA, 2022).

A similar situation is being experienced in Turkey in parallel with the population growth and urbanisation phenomenon in the world. According to the data of Turkish Statistical Institute (TÜİK) 2023; while the ratio of urban population to total population was 64.9% in 2000, this ratio reached 93% in 2023 (TÜİK, 2023). The fact that 81% of the energy used in dwellings in Turkey is used for heating purposes shows that dwellings in Turkey are insufficient in terms of energy efficiency. It has been revealed that Turkey's energy saving potential has reached 50% in buildings (Pamir, 2017).

In order to use energy efficiently in buildings, there are many studies on the energy efficiency of wall elements, opaque components formed by insulation materials and transparent components formed by glass and joinery (Vincelas & Ghislain, 2017; Kon, 2018; Alsayed & Tayeh, 2019; Aydin & Biyikoglu, 2020; Urbikain, 2020; Rosti et al., 2020; Mousavi Motlagh et al., 2021; Aktemur et al., 2021; Sayadi et al., 2022). In the literature, it has been observed that there are studies on building envelope design, which is generally one of the energy efficient building criteria, and energy efficiency calculations are made by considering the building heating load.

In this study; the effect of photovoltaic panel system application to selected base buildings as well as the improvement of the lighting system on energy performance in an island-based residential compound in Antalya, which is located in the Hot-Humid Climate Zone, is analysed. The most distinctive feature that distinguishes the study from other studies is that energy efficiency is not evaluated at the level of a building, floor or neighbourhood, but at the island-based settlement level. In addition, since the heating needs of the buildings in Antalya, which is located in the Mediterranean Climate Zone, are widely met with electrical energy, the analyses are repeated for the case where electrical energy is used as well as natural gas in heating within the scope of the study and energy efficiency is examined according to the type of fuel used in heating.

Improvement of Lighting System in Energy Efficient Residence Design

When the energy consumption of buildings is analysed, it is seen that electricity is mostly consumed by electrical equipment within the scope of mechanical systems. Daylight, motion and presence sensors and automatic time control in electrical systems provide savings in energy consumption. According to ASHRAE 90.1-2010 standard, if programmed time control is used in the lighting system, 10% and 15% of the electrical energy consumed for lighting is saved if presence sensors are used. Energy saving and effective use of energy can be achieved with a lighting that is suitable for the purpose, of high quality and provides good visual conditions without exceeding the required illuminance level in buildings (Yüksel, 2019).

Photovoltaic Panel System Application in Energy Efficient Residential Design

PV (photovoltaic) panels are systems that generate electrical energy from the sun to meet the electricity requirements of buildings for heating, cooling and lighting. These panels, which are used to convert solar energy into electrical energy, are one of the most important renewable energy technologies in energy efficient building design since they do not cause greenhouse gases during use. It has not become widespread in our country due to high initial investment costs and lack of necessary information studies (Kılıç Demircan & Gültekin 2015; Kılıç Demircan & Gültekin, 2017). Roof applications of PV panels are applied in two different ways as mounted and integrated PV systems. Building integrated PV systems replace the roof structure and form the shell itself (Ulusoy Şentürk & Altın, 2014), (Figure 1).

Figure 1: PV panel roof applications; a) terrace roof PV systems, b) integrated PV systems, c) mounted PV systems (Daima Enerji, 2023).

Method

In the study, an island-based campus project in Antalya, which is located in the Mediterranean Climate Zone and classified in the 1st Degree Day Zone according to the Turkish Standards Institute (TS 825), with a hot-humid climate, was selected as a sample. The extent to which the energy need can be reduced by improving the lighting system in the buildings selected in the island-based campus and the extent to which the energy need can be met by photovoltaic panel application are examined separately.

Within the scope of the study; Block B, Block D and Block F were preferred as "Base Building" in order to examine the improvement of the lighting system and photovoltaic panel application by taking into account factors such as orientation, location, facade area, number of storeys, transparent surface ratio of the buildings in the island-based campus. Block B, Block D and Block F were modelled according to the current situation and "Base Building Models" were created. "Design Building Models" were created by taking into account the power densities recommended by the American Society of Heating, Refrigeration and Ventilation Engineers (ASHRAE) according to the spaces and using LED (Lighting Emited Diodes) bulbs instead of saving bulbs (compact fluorescent bulbs) only in the base buildings so that the lighting fixtures remain constant.

Energy cost, emission and saving ratios were obtained by comparing the energy consumption between the Base Building Models and Design Building Models. The analyses were performed by using meteorological database which is a dynamic thermal simulation programme and DesignBuilder dynamic simulation tools with 3D modelling capability. The cost of improving the lighting system in the Base Buildings was calculated and cost analysis was made. Cost information of saving and Led bulbs were obtained from the companies in the market.

There is no photovoltaic panel system to generate electricity from solar energy in the base buildings considered in the study. In the study, it is aimed to obtain electricity generation from solar energy by designing photovoltaic panels in base buildings. In this context, PV electricity generation report of the base buildings was obtained with the help of the PV simulation software provided by cw-energy company in order to design solar PV systems. PV system cost was obtained from the companies in the market. Cost analyses were made for each block and presented in tables.

Within the scope of the study, the analyses were repeated by using electric energy as well as natural gas as heating energy in the buildings. In the study, 2 Base Building models were created for each block according to the type of energy used in heating. In the case where natural gas is used as heating energy, the "Design Building-1" model was obtained by improving the lighting system and applying photovoltaic panel system to the "Base Building-1" (heating natural gas; cooling electricity) model. In the case where electric energy is used as heating energy, "Design Building-2" model was obtained by improving the lighting system and applying photovoltaic panel system to the "Base Building-2" (heating electricity; cooling electricity) model.

Findings

The study area has been selected as an island-based urban transformation project and consists of 6 blocks, 317 houses and a total construction area of 37.647 m^2. Block B consists of 10 floors and has 76 independent sections with a total net usage area of 4743,7 m^2. D block has 11 floors, 41 independent sections, with a total net usage area of 5102,4 m^2. Block F has 9 floors, 51 independent sections, total 5201,3 m^2 net usage area. Within the scope of the study; Block B, Block D and Block F were preferred as "Base Buildings" by considering factors such as orientation, location, façade area, number of storeys, transparent surface ratio of the buildings in the island-based campus. The island-based residential compound representing the energy consumption behaviour of the base buildings was modelled (Figure 2).

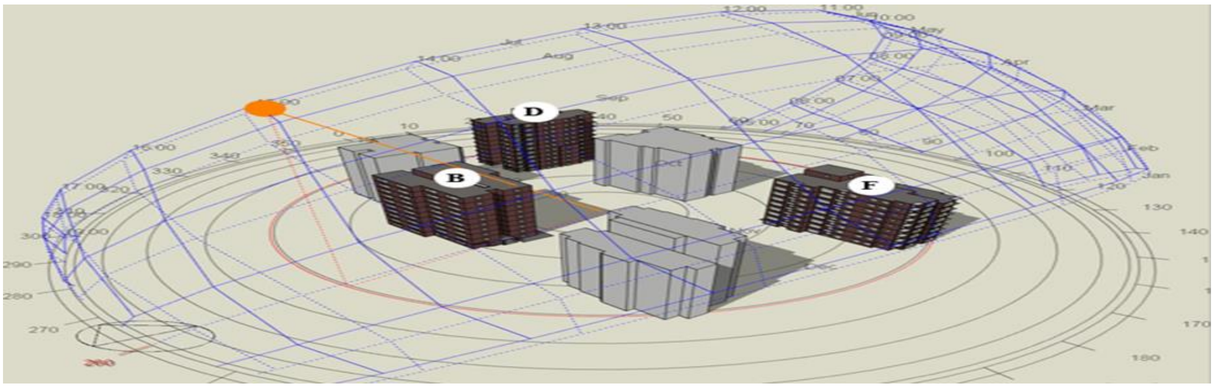

Figure 2: Island-based model image of the study area.

Heating and cooling load calculations for Antalya province where the Base Buildings are located, ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) recommended by ASHRAE (American Society of Heating, Refrigerating and Air-

Conditioning Engineers) according to ASHRAE 90.1-2010 standard ASHRAE Climate Zone 3A Region (Turkey's 1st Climate Zone) climate data were used. Heating in the buildings is done with boiler+radiator and split air conditioner (7800W, COP:3.20), cooling is done with split air conditioner (7100W, EER:3.00). In the calculations, the indoor air temperature comfort value is taken as 22°C for the heating period and 25°C for the cooling period. Natural ventilation is designed in the buildings and air exchange coefficient (ACH) is taken as 0.5(1/h). Base Buildings and Design Buildings are modelled according to ASHRAE Standard residential use profile. In this context, the number of people using the buildings is taken as 20 m^2/person and the operation hours/days are taken as continuous, 7/24.

Lighting System Improvement

Only the bulb type and lighting power density have been changed so that the electrical appliances used in the base buildings remain the same. Improvements were made in the lighting system in the base buildings by using 9W and 14W LED (Lighting Emited Diodes) bulbs, which have approximately equivalent luminous intensity (lumens) and more energy efficiency, instead of 12W and 20W saving bulbs (compact fluorescent bulbs). The electrical equipment power density value did not change since there was no electrical equipment change after the improvement. Electrical equipment power density was taken as 6 W/m^2 as in the Base Buildings. The light bulbs used in the lighting system before and after the retrofit and the values of the lighting power density in the buildings before and after the retrofit are shown in Table 1 and Table 2, respectively. Energy cost, emission and saving rates were obtained by performing hourly analyses between the existing building models (Base Building) and Design Building models with the Design Builder simulation programme. The annual energy consumption values of the Base Buildings and Design Buildings, energy saving rates and the increase in the cost of implementation are presented in Table 3.

Table 1. Lighting system improvement scenarios.

Design Scenario	Bulb Type	Application Areas						
		Parlour	Kitchen	Bedrooms	Antre	Bathroom 1	Bathroom 2	Balcony
Current Status	Tasarruflu	20W	20W	20W	20W	12W LED	12W	20W
Design Scenario	LED	14 W	14 W	14 W	14 W	12 W	9 W	14 W

Table 2. Values of building lighting power density before and after improvement.

Mahal	Base Buildings (W/m²)	Design Buildings (W/m²)
Apartment	12	7,8
Corridors/Common Areas	3,2	2,3
Mechanical Room	8	5,6

Table 3. Comparison of lighting costs of base buildings and design buildings.

Account Items	Base Building 1	Design Building 1	Base Building 2	Design Building 2

Block B				
Energy Consumption (kW)	351880,65	333499,09	311385,92	288870,39
Bulb Cost ($)	2195,74	3631,08	2195,74	3631,08
Energy Savings (kW)	5,22%		7,23%	
Cost Increase ($/m²)	0,30		0,30	
Block D				
Energy Consumption (kW)	325667,92	308548,74	275640,13	255948
Bulb Cost ($)	1183,80	1958,24	1183,80	1958,24
Energy Savings (kW)	5,26%		7,14%	
Cost Increase ($/m²)	0,15		0,15	
Block F				
Energy Consumption (kW)	343797,43	327085,15	301847,08	281223,79
Bulb Cost ($)	1469,97	2431,67	1469,97	2431,67
Energy Savings (kW)	4,86%		6,83%	
Cost Increase ($/m²)	0,18		0,18	

When Table 3 is analysed, it is seen that if LED bulbs are used instead of saving bulbs used in the Base Buildings, total energy savings ranging from 4.9% to 7.2% are provided in the buildings against the cost increase of approximately 18.9 $ per apartment.

Photovoltaic Panel Design and Application

In the study, it is aimed to obtain electricity generation from solar energy by designing photovoltaic panels in Base Buildings. For the terrace roof PV system applied to the Base Buildings, the optimum design was realised by considering the placement and orientation of the panels, the location where the system will be installed and the shading effect (Figure 3).

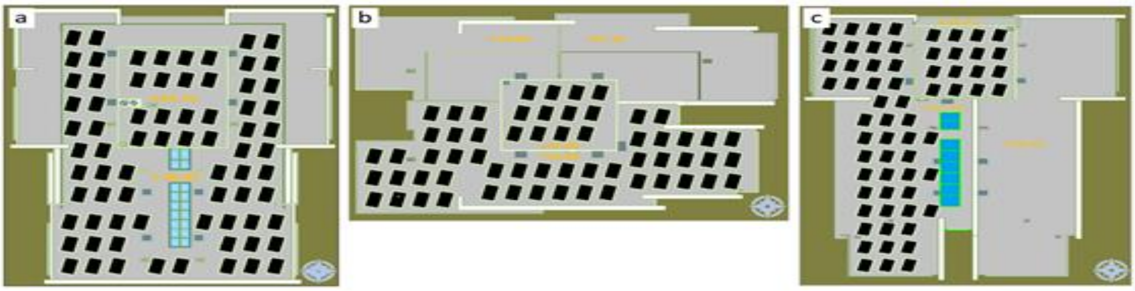

Figure 3: Photovoltaic panel application in base buildings; a) Block B base building, b) Block D base building, c) Block F base building.

The annual energy amount to be produced by the PV system was calculated with the PV simulation software offered by cw-energy company. The location of the building, meteorological data, all system components and system losses were defined as input to the Solar PV programme and 8760 hours of simulation was performed. As a result of the simulation, the amount of electricity generated in the Base Buildings is presented in Table 4.

Table 4. Photovoltaic panel system information applied to base buildings.

PV System Information	Unit	B Block Design Building	D Block Design Building	F Block Design Building
Power	kWp	25,4	18,9	20,4
Number of Panels	Quantity	74	60	64
Roof usage area	m²	220	108	115
Amount of electricity produced with PV	kWh/year	38493,17	28565	30929
Installation cost	$	25553,90	18963,33	20532,82
Cost increase	$/m²	4,9	3,4	3,6
Savings from mains electricity	$/year	3312,17	2457,89	2661,30
System amortisation time	year	7,7	7,7	7,7

In B-D-F Design Building-1, where natural gas is used for heating and electrical energy is used for cooling, the ratio of meeting the annual energy consumption with the solar energy system is 14%, 12%, 11%, respectively. In B-D-F Design Building-2, where heating and cooling are met by using electrical energy, these values are 12%, 10%, 10%, respectively. It is seen that with the application of photovoltaic panel system in the blocks, an average of 249.922 Tn CO^2 emission can be prevented in each block. It is known that the lifetime of the photovoltaic panel system is 25 years. In this case, considering the depreciation periods of photovoltaic panel systems, it can be said that approximately 12% of the electricity used in the blocks for about 17 years with the solar energy system can be met almost free of charge every year.

Results

In this study, the effect of the improvement of the lighting system and the design of photovoltaic panels on the energy performance of the building in the buildings selected in the island-based campus in Antalya, located in the Mediterranean Climate Zone, is analysed. Analyses were made on the energy consumption data of heating, cooling, lighting and ventilation systems in the Design Building Models created after the improvement of the lighting system in the base buildings. As a result of the analyses, it was seen that annual energy savings between 32.5% and 33.0% were achieved in lighting-related energy consumption, and the total energy savings reached 7.2% depending on the type of fuel used. In case of integrating photovoltaic panels in the base buildings, it is seen that annual energy consumption can be met by solar energy between 10% and 14%. The cost of upgrading the lighting system and the cost of integrating photovoltaic panels were calculated to be 0.2 $\$/m^2$ and 4.0 $\$/m^2$, respectively.

The study is unique in that design parameters such as the location, position and distance between buildings are taken into consideration in island-based settlements. Another important feature of the study is that the heating needs of the buildings in Antalya are widely met with electrical energy, so the analyses in which electrical energy is used in addition to natural gas in heating are carried out within the scope of the study.

As a result, it is concluded that the bulbs to be preferred in the lighting system are an important parameter to be considered when the cost of improvement of the lighting system in the buildings selected in the island-based settlement in Antalya, which is located in the Mediterranean Climate Zone, and the energy saving rates obtained are considered. It has been observed that energy costs can be reduced as a result of the use of photovoltaic panel system in the houses located in the Mediterranean Climate Zone. In the study, it is thought that the results will contribute significantly to the academia and the construction sector and will be guiding since it is focused on sustainable energy and the energy-cost relationship with the improvement of the lighting system and the application of photovoltaic panel system.

References

Aktemur, C., Bılgın, F., & Tunçkol, S. (2021). Optimisation on the thermal insulation layer thickness in buildings with environmental analysis: An updated comprehensive study for Turkey's all provinces. *Journal of Thermal Engineering*, *7*(5), 1239-1256.

Alsayed, M. F., & Tayeh, R. A. (2019). Life cycle cost analysis for determining optimal insulation thickness in Palestinian buildings. *Journal of Building Engineering*, *22*, 101-112.

Aydin, N., & Biyikoglu, A. (2020). The effect of cooling load on optimum insulation thickness in residential buildings. *Isı Bilimi ve Teknigi Dergisi-Journal of Thermal Science and Technology*, *40*(2), 281-291.

Daima Enerji. (2024, March 31). *Fotovoltaik/Güneş enerjisinden elektrik üretimi*. https://www.daimaenerji.com/

Demir, H., Çıracı, G., Reyhan, K., & Ünver, Ü. (2020). Aydınlatmada enerji verimliliği: Yalova Üniversitesi Mühendislik Fakültesi durum değerlendirmesi. *Uludağ Üniversitesi Mühendislik Fakültesi Dergisi*, *25*(3), 1637-1652.

Demircan, R. K., & Gültekin, A. B. (2017). Binalarda pasif ve aktif güneş sistemlerinin incelenmesi. *TÜBAV Bilim Dergisi*, *10*(1), 36-51.

European Commission. (2022, April 4). *2030 climate & energy framework*. https://ec.europa.eu/clima/eu-action/climate-strategies-targets/2030-climate-energy_framework_en.

IEA 2022. (2023, March 5). *World Energy Outlook 2022*, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2022

Kılıç Demircan, R., & Gültekin, A. B. (2015). Binalarda pasif ve aktif güneş sistemlerinin incelenmesi. In *2nd International Sustainable Buildings Symposium sunulan bildiri, Gazi Üniversitesi, Ankara. Erişim adresi: http://www. isbs2015. gazi. edu. tr/belgeler/bildiriler/839-847. pdf.*

Kon, O. (2018) Calculation of fuel consumption and emissions in buildings based on external walls and windows using economic optimization. *Journal of the Faculty of Engineering and Architecture of Gazi University*, *33*(1), 101-113.

Mousavi Motlagh, S. F., Sohani, A., Djavad Saghafi, M., Sayyaadi, H., & Nastasi, B. (2021). Acquiring the foremost window allocation strategy to achieve the best trade-off among energy, environmental, and comfort criteria in a building. *Energies*, *14*(13), 3962.

Pamir, N. (2017) *Enerjinin iktidarı*. Hayygrup Yayınevi.

Rosti, B., Omidvar, A., & Monghasemi, N. (2020). Optimal insulation thickness of common classic and modern exterior walls in different climate zones of Iran. *Journal of Building Engineering*, *27*, 100954.

Sayadi, S., Hayati, A., & Salmanzadeh, M. (2021). Optimization of window-to-wall ratio for buildings located in different climates: An IDA-indoor climate and energy simulation study. *Energies*, *14*(7), 1974.

TÜİK 2023 (2024, April 4). *Adrese dayalı nüfus kayıt sistemi sonuçları, 2023,* https://data.tuik.gov.tr/Bulten/Index?p=Adrese-Dayali-Nufus-Kayit-Sistemi-Sonuclari-2023-49684#:~:text=T%C3%BCrkiye'de%202022%20y%C4%B1l%C4%B1nda%20%93,dan%20%257'ye%20y%C3%BCkseldi.&text=%C4%B0stanbul'un%20n%C3%BCfusu%2C%20bir%20%C3%B6nceki,655%20bin%20924%20ki%C5%9Fi%20oldu

Ulusoy Şenyurt, S., & Altın, M. (2014). Enerji etkin tasarımın çatı ve cephelere yansıması. *7. Ulusal Çatı & Cephe Sempozyumu*.

Urbikain, M. K. (2020). Energy efficient solutions for retrofitting a residential multi-storey building with vacuum insulation panels and low-E windows in two European climates. *Journal of Cleaner Production*, *269*, 121459.

Vincelas, F. F. C., & Ghislain, T. (2017). The determination of the most economical combination between external wall and the optimum insulation material in Cameroonian's buildings. *Journal of Building Engineering*, *9*, 155-163.

Yüksel, T. (2019). *Mevcut bir binanın yenilenmesinde pasif ve aktif seçeneklerin enerji verimliliği ve maliyet acısından değerlendirilmesi*. [Yüksek lisans tezi, Yıldız Teknik Üniversitesi]. https://tez.yok.gov.tr/UlusalTezMerkezi/tezDetay.jsp?id=-_P_Kl0Gw4XTIVa0bytcVQ&no=C4qk86CidZdb5xkjZIYpzA

Unveiling Climate Complexity: TS825,2013 and Koppen Geiger Influences on Building Envelope and Energy Consumption in Turkish Cities

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Abstract

This study aims to investigate the relationship between climate classifications (TS825,2013, and Koppen Greiger) and their impact on energy consumption and construction efficiency in three Turkish cities. The effect of varying climates on a structure's energy performance is made clear through model analysis and literature evaluation. A thorough assessment of the literature creates a theoretical foundation for modeling. Energy performance is simulated for typical structures in each city using Design Builder software. The analysis measured how building envelope and energy consumption patterns are impacted by different climate classifications. Forecast results indicated different energy patterns in cities according to climatic categories. According to this research, TS825,2013 provides a more accurate representation of the climate than Koppen Greiger, assisting with energy predictions. This study focused on cities with comparable TS825,2013 but distinct Koppen Greiger classifications to inform future construction design and energy strategies specific to each site's climate. This study presents a novel methodology for assessing urban energy performance in Trabzon, Istanbul, and Sanliurfa, integrating the ASHRAE database. The study examines climate classification's impact on building energy usage and emphasizes the necessity for regular zone re-evaluation. The research offers actionable insights for optimizing energy-efficient building design and mitigating urban energy consumption.

Keywords: *building energy consumption, building envelope, energy efficiency, Koppen Greiger climate classification, TS 825.*

Introduction

Classifying climates helps simplify the representation of expected climate conditions, essential in building design and energy efficiency programs (Gupta et al., 2023). Climate classification also helps to develop building energy codes and standards and aids urban planning and development (Stevanović, 2013). Climate classification methods vary in their approaches to parameters and variables, and recent studies have considered building energy performance indicators and degree days (Taleghani et al., 2013; Van Den Wymelenberg, 2012). Degree days provide a straightforward and consistent measurement of building energy consumption and are commonly used in climate classification for building energy efficiency (Gaygusuzoglu & Bakis, 2017).

Koppen Greiger is an empirical system that categorizes the world's climate into discrete groups and subgroups according to temperature and precipitation (Kottek et al., 2006). These groups are further subdivided into smaller groups that offer more specific insights into regional climate variations (Every et al., 2020). The Koppen-Geiger climate classification system is used globally to create energy-efficient building guidelines. This system explicitly specifies envelope design requirements and offers valuable insights for creating energy-efficient buildings adapted to various climatic conditions. On the other hand, ASHRAE climate classification combines degree days with annual precipitation data to determine base temperatures (Bhatnagar et al., 2019; Indraganti & Boussaa, 2017). However, the ASHRAE system cannot discriminate between the climate characteristics of the Yunnan-Guizhou plateau and the Yangtze River drainage basin (Bhatnagar et al., 2018). In addition to these classification systems, the Turkish Standard Institute has governed TS825 as the mandatory thermal insulation standard for buildings in Turkiye since 2008, but 85% of the current building stock still needs to satisfy the standard's minimal requirements (M. Altun & Akcamete, n.d.; Doç et al., n.d.). Further, the Energy Efficiency Law was passed in 2007 and requires existing buildings to increase their energy efficiency (Schimschar et al., 2016a).

Several studies exist about climate classification systems. Recent research addresses the best building envelope design parameters for energy efficiency that were determined by considering elements like window-to-wall ratio, glazing type, insulation thickness, and orientation by different climate classification systems (Altun, 2022; Congedo et al., 2021; Mitz-Hernandez et al., 2022; Song et al., 2022). One of the most comprehensive studies covers a range of climates by focusing on the Koppen-Greiger global study (Li et al., 2023). Another recent study examined the consequences of climate change on building energy use by addressing the Koppen climate classification system (Gutai & Kheybari, 2020). Research showed that the Koppen climate classification has gained recognition for its role in energy performance and conservation, as well as building retrofitting and design optimization (Andre et al., 2023).

Further, recent studies have reviewed building codes that set minimum and maximum U-values for building envelopes (Ounis et al., 2022). These studies have found that climate variations significantly impact occupant complaints. European residential buildings' wall thermal insulation thicknesses impact their energy efficiency (Ounis et al., 2022). Massive walls perform better than lightweight ones in most cases, according to a study by (Ounis et al., 2022). The authors implemented case study research using the Revit Add-in Dynamo application to perform efficient TS 825 standard analysis, significantly reducing energy consumption. Using a tracing technique and energy modeling, researchers found that wall core location and material type affect energy consumption (Süer & İlerisoy, 2022). When the studies are reviewed, it is clear that there is a significant research gap in systematically comparing building code requirements across various climate zones to design energy-efficient building envelopes. For this reason, the research objective of this study is to (1) evaluate the U-values for walls, windows, and roofs in three Turkish cities (i.e., Istanbul, Trabzon, and Sanliurfa) according to TS 825:2013 and (2) compare the U-values according to the ASHRAE and Koppen Grieger classification. In this scope, each city's weather data for 2018 and 2021 was examined, and the heating and cooling requirements in two distinct weather scenarios were investigated.

Research Objectives and Methodology

A systematic literature review and case study fulfilled the research objective. In the literature review, the following keywords were used: "building energy performance," "building energy consumption," "climate classification," "TS825," "Koppen Greiger," "ASHRAE," "EPBD," "building envelope," and "U-factor." The review, limited to journal articles and review papers, spanned the interval 2010-2024 in the "Web of Science" database, focusing on categories related to Building and Construction Technology, Civil Engineering, and Architecture. Forty-two articles were kept for the literature review after the obtained bibliographic data was pre-processed. The remaining data, which included hourly weather data and climate classifications for Turkey based on Koppen, TS825, and ASHRAE, were obtained from weather data, building codes, and ASHRAE.

Data on the climate and weather of the chosen cities was gathered, and TOKI's plan was modeled in Design Builder as a one-story, four-story case study building. The building's total area was modeled at 268.21 m2, and the net conditioned building area was 263 m^2. The U-values needed for ASHRAE, TS825, and cost-optimal were compiled. The cost-optimal U-value extracted from the report result has been provided by ECOFYS and ordered by IZODER in the context of EPBD (Schimschar et al., 2016). Subsequently, 18 scenarios were defined for three cities (i.e., Istanbul, Trabzon, and Sanliurfa), each with two sets of weather data and two U-values, resulting in two envelope scenarios for each city. After that, these scenarios were simulated to determine the heating and cooling demands. The simulation results allowed a comparative analysis to determine which climate zones and scenarios contributed to lower energy consumption.

Climate Condition and Climate Classification

The climate condition of Turkiye regarding TS 825 was divided into four regions. The considered variables for classification are degree day. Regarding TS 825.2013, Istanbul, Trabzon, and Sanliurfa belong to the second region. The detailed information about each region is addressed in Table 1. Each parameter is clarified as follows:
UD=Wall u-value
UT = Roof u-value
Ut= Ground floor u-value
Up= window u-value

Table 1. U-Value requirements considering TS825.

	UD (W/m2K)	UT (W/m2K)	Ut (W/m2K)2	Up (W/m2K)
1. Zone	0.66	0.43	0.66	1.8
2. Zone	0.57	0.38	0.57	1.8
3. Zone	0.48	0.28	0.43	1.8
4. Zone	0.38	0.23	0.38	1.8
5. Zone	0.36	0.21	0.36	1.8

Considering the results of a comparative analysis accomplished by the Energy Performance of Buildings Directive (EPBD) regarding TS825 and ASHRAE to optimize the required U-value for the building envelope, the U-value provided by TS825 has been revised (Table *1*). The research scenarios were determined by considering extracted U-values regarding TS-825, ASHRAE, and cost-optimal for evaluating accurate climate classification and corresponding building codes in the heating and cooling district. The prerequisites of the scenario are given in Table 2.

Table 2. Research scenario prerequisites.

City	TS 825	hourly weather data	ASHRAE	Koppen	Envelope	U-value regarding ASHRAE	U-value regarding TS825	U-value regarding cost-optimal
Istanbul	2	2018	3C	Cfa	Wall	0.701	0.6	0.28
		2021	3A	Csa	Window	3.69	2.4	1.8
					Slab	0.7	0.4	0.19
Trabzon	2	2018	5A	Dfb	Wall	0.513-0.701	0.6	0.27
		2021	3C	Cfa	Window	3.12-3.69	2.4	1.17
					Slab	0.75	0.4	0.2
Sanliurfa	2	2018	2B	Bsk	Wall	0.857-0.701	0.6	0.27
		2021	3A	Csa	Window	3.69-4.26	2.4	1.17
					Slab	0.73	0.4	0.2

Results and Discussions

The hourly weather data for each city were obtained from ASHRAE weather data open source for 2018 and 2021—the .epw files were imported to the design-builder, and further simulation was accomplished for each scenario. All the obtained data evaluated separately are addressed in further sections to provide a precise approach to affecting the research variables on total energy usage for heating and cooling.

Cooling District

Regarding the simulation results, the obtained District cooling amount for all scenarios was collected and demonstrated in
Figure *1*. As the main scenario, the requirements for TS825 were conducted first for each city. Considering the results in

Figure *1*, the district cooling for cities is different according to 2018 weather data compared to 2021. The drastic difference noted for TS825 in cooling consumption is more evident than in ASHRAE and cost-optimal scenarios.

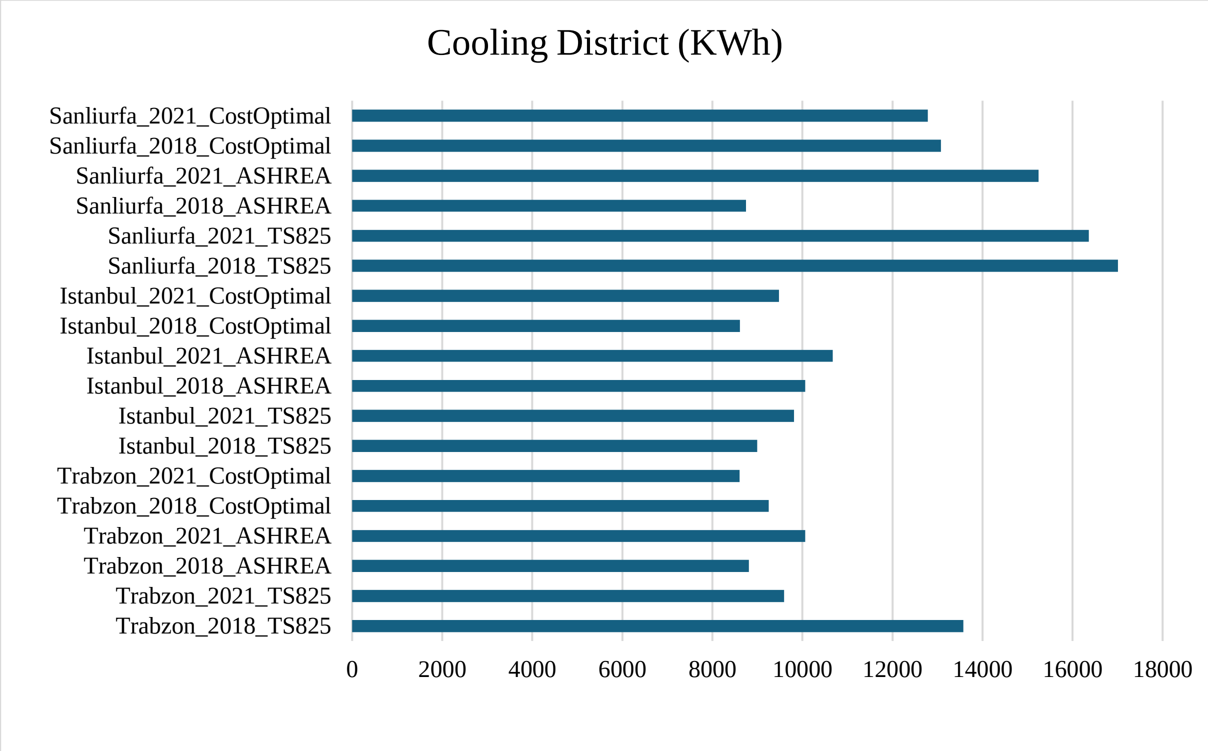

Figure 1: Cooling district comparison.

The cooling end use for Trabzon using 2018 weather data indicates that ASHRAE building envelope requirements are more appropriate for this climate, noting a remarkable reduction in the cooling district by approximately 35%. To have this, considering the results for 2021, cooling end use for Trabzon has the optimal amount (8600 KW) for the cost-optimal scenario, and ASHRAE has the maximum end use amount (10065 KW) for cooling among TS925 and cost-optimal scenarios.

Comparing the results for Istanbul, the cost-optimal scenario has lower cooling consumption than TS825 and ASHRAE. The same effect was evident for 2021 weather data. The cooling district of the cost-optimal scenario is lower than TS825 by 2-4% for 2018 and 2021 weather data, respectively. Interestingly, ASHRAE has higher cooling usage among other scenarios.

As a result, as mentioned in previous sections, cost-optimal requirements have been considered Koppen classifications, which are more correlated with the recent weather data. The CDD and HDD for each city have been changed significantly, which leads to decreased/increased energy demand for buildings. It is worth noting that regarding Trabzon climate conditions, the ASHRAE building code provides energy efficiency due to the 2018 weather data, while the optimal scenario is more appropriate for 2021 weather data conditions, further, for Istanbul, 2018 and 2021 weather data and considering the climate condition cost optimal scenario led to efficient building envelope design.

On the other hand, the results for the cooling district for Sanliurfa seem complicated. Opposite to different cities, the result for 2018 regarding TS825 is higher than that for 2021, which addresses cooling demand reduction. The most efficient cooling demand belongs to ASHRAE, considering 2018 weather data, followed by cost-optimal for 2021.

Heating District

Concerning
Figure 2, considering the 2018 and 2021 weather data, the district heating amount for Trabzon has the lowest energy consumption using ASHRAE building envelope requirements. ASHRAE requirements have achieved a 16-58% reduction in heating demand.

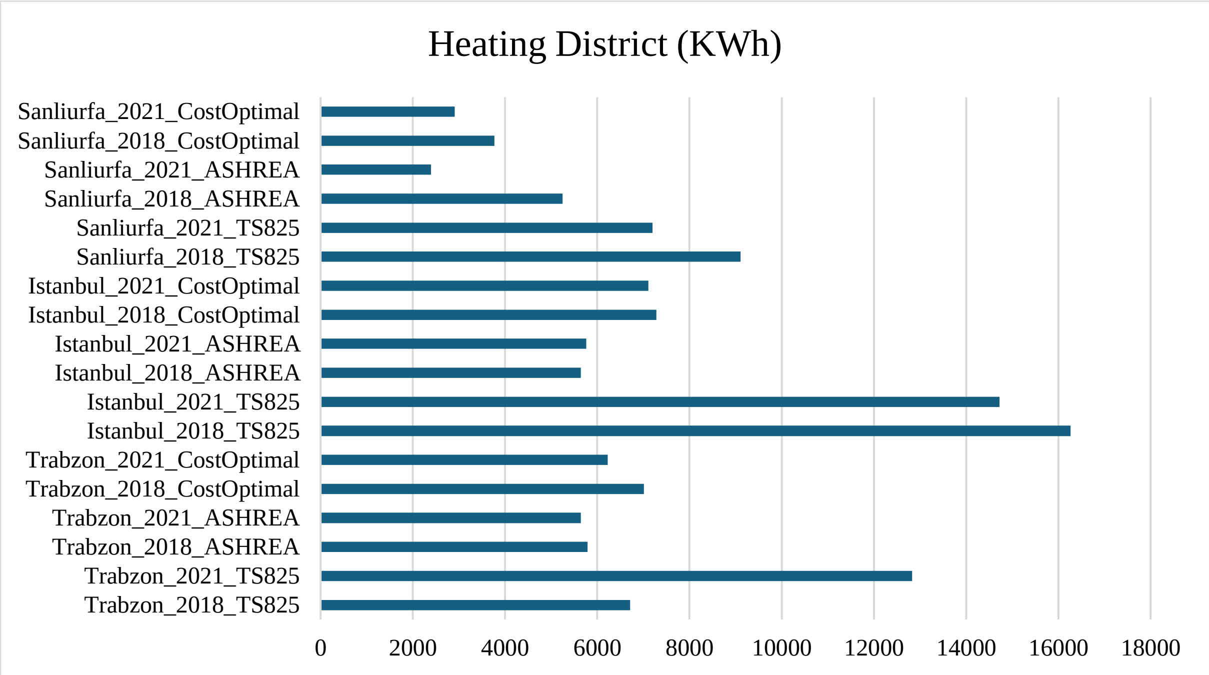

Figure 2: Heating district comparison.

The result for Istanbul in 2018-2021 is the lowest heating energy consumption compared to the cost-optimal, followed by TS825. The reduction achieved by ASHRAE requirements is between 58%-64%. The simulation result regarding 2021 weather data for TS825 in Trabzon should have dramatically higher heating energy consumption than other scenarios.

Regarding Istanbul, the district heating amount for 2018 and 2021's remarkably higher consumption range belongs to TS825. The TS 825 climate classification for Istanbul might be reconsidered due to its inefficient energy performance. Additionally, the results prove that after 2021, the climate zone for Trabzon might have been revised as the TS825 requirements' effect for 2018 weather data was not extremely higher than the results of other scenarios.

Total Energy Consumption and Comparison

According to previous sections and evaluating heating and cooling consumption separately, it is worth noting that the total energy consumption should be considered and investigated to obtain the detailed and comprehensive interactions between accurate climate classification and building code effect on building energy efficiency. As demonstrated in

Figure 3, the cooling and heating energy consumption derived from all analyses results to evaluate and assess their effect on total energy consumption. Some scenarios affect heating consumption positively, and some impact district cooling amounts similarly. Among all scenarios, the scenario in Trabzon followed ASHRAE requirements regarding 2018 weather data and has the lowest total energy consumption amount (14596 KWh, 54 KW/m^2), followed by Trabzon 2021_cost optimal (14884 Kwh,55,49 KW/m^2). The total amount for scenarios evaluated in Sanliurfa has higher total energy consumption(26116.53 KWh,91.24 KW/m^2) than scenarios resulting in Trabzon(22420.79 KWh, 78.33 KW/m^2).

Regarding
Figure 3, ASHREAs' scenario provides an efficient building rather than TS825 and is cost-optimized. ASHRAE provided appropriate building envelope design requirements, resulting in lower energy consumption for 2018 and 2021 weather data. The climate classification regarding ASHRAE proved to be more accurate than other classification methods for Istanbul. ASHRAE and cost-optimizing building codes resulted in energy consumption reductions, corresponding to 2018 weather data. The four lowest total energy consumption belong to Sanliurfa_2018_ASHREA, followed by Trabzon_2018_ASHREA, Trabzon_2021_costoptimal, and Sanliurfa_2021_costoptimal.

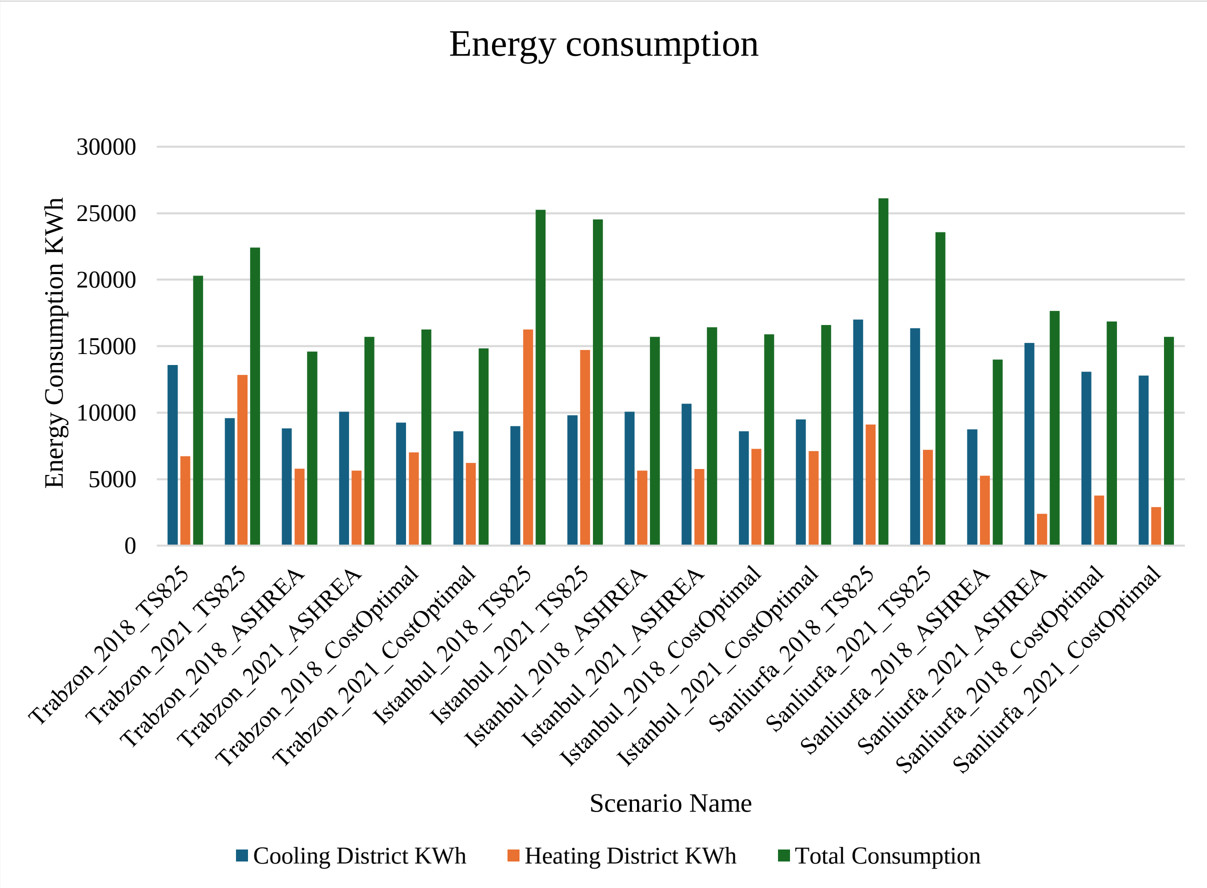

Figure 3: Total energy consumption evaluation.

According to recent weather data for Sanliurfa and Trabzon, these results led to the accuracy of cost-optimal building codes. The same theory was evidenced for Istanbul; ASHRAE and cost-optimal resulted in lower total energy consumption using 2018's weather data. Hence, the same differences were observed for 2021's weather data in Istanbul's total district.

As a result, this study emphasizes the need for a more thorough evaluation of the factors involved in climate classification and the creation of building energy codes. The fact that degree days are now included in ASHRAE's classification criteria emphasizes how crucial accurate climate data are becoming. The past three years' variations in Heating Degree Days (HDD) and Cooling Degree Days (CDD) highlight the importance of precise and data-driven climate information. Ultimately, the results indicate that climate classification and building energy codes can be valuable instruments for preliminary design assessment.

It should be noted that the heating district in Sanliurfa is negligible compared to the cooling district. The u-value requirement provided by TS825 resulted in the highest cooling district concerning 2018 and 2021 weather data, respectively. On the other hand, the highest heating district was observed on Sanliurfa_2018_TS825 and Sanliurfa_2021_TS825. Regarding the indicated results, the cooling demand for 2021 has increased remarkably.

Conclusions

This study extensively investigated the energy performance of Trabzon, Istanbul, and Sanliurfa districts under different climate scenarios. ASHRAE's open-source database provided the hourly weather data for 2018 and 2021, and the Design-Builder program was used to perform the simulations. This study highlights the importance of accurately classifying climates when analyzing building energy performance. This study contributes significantly to urban energy performance analysis by thoroughly investigating the energy dynamics of districts in Trabzon, Istanbul, and Sanliurfa under different climate scenarios. Through a meticulous investigation, the study highlights the profound impact of climate classification on building energy consumption, providing actionable insights for key stakeholders such as policymakers, architects, and engineers and highlighting the need to routinely reevaluate climate zones to ensure that they align with changing weather patterns and maximize the design of energy-efficient buildings.

Notwithstanding inherent limitations, including the lack of meticulously detailed meteorological information, the study underscores the importance of integrating contemporary meteorological data into climate classification frameworks to implement sustainable building practices.
The key findings of this study are summarized below:
District Cooling:

- There were notable differences in district cooling consumption between the scenarios.
- In 2018, Trabzon found the ASHRAE building envelope requirements highly effective.
- The study results showed an impressive 35% reduction in cooling consumption compared to alternative situations.
- For Istanbul and Sanliurfa, the cost-optimal scenario outperformed ASHRAE, demonstrating the importance of current climate data for classification.

District Heater:
For district heating in Trabzon, ASHRAE requirements proved the most effective.

- A significant 16-58% reduction in energy consumption was achieved.
- Istanbul's increased energy consumption due to the TS825 climate classification indicates the need for a review.
- Studies highlight the possibility of updating climate zones based on current meteorological information.

Comparison of total energy consumption:

- Examines total energy use, including both heating and cooling.
- Based on 2018 weather data, the ASHRAE scenario showed the lowest total energy consumption in Trabzon(14596 KWh, 54 KW/m^2).
- The cost-optimal scenario for 2021 was close behind, highlighting the importance of accurate climate classification.
- ASHRAE in Istanbul consistently outperformed other scenarios, demonstrating the value of current weather information in determining climate classification.

Based on the observed energy performance deficiencies, the results indicate that the climate classification for Sanliurfa and Istanbul in TS825 may need re-evaluation. In addition, the study suggests that Trabzon's climate zone may have changed as the TS825 requirements had a less noticeable impact on weather data from 2018.

Although the study provided important insights, it is critical to address the limitations by securing more accurate meteorological data and using sophisticated simulation software in subsequent research. In addition, more research is required to understand the dynamic interactions between different climate classification parameters.

References

Altun, M., & Akcamete, A. (n.d.). *Application of TS 825 Turkish Thermal Insulation Standard Using BIM*. https://www.researchgate.net/publication/334112494

Andre, M., Bandurski, K., Bandyopadhyay, A., Bavaresco, M., Buonocore, C., de Castro, L., Hahn, J., Kane, M., Lingua, C., Pioppi, B., Piselli, C., Spigliantini, G., Vergerio, G., & Lamberts, R. (2023). Practical differences in operating buildings across countries and climate zones: Perspectives of building managers/operators. *Energy and Buildings*, *278*. https://doi.org/10.1016/j.enbuild.2022.112650

Bhatnagar, M., Mathur, J., & Garg, V. (2018). Determining base temperature for heating and cooling degree-days for India. *Journal of Building Engineering*, *18*, 270–280. https://doi.org/https://doi.org/10.1016/j.jobe.2018.03.020

Bhatnagar, M., Mathur, J., & Garg, V. (2019). Climate zone classification of India using new base temperature. *Building Simulation Conference Proceedings*, *7*, 4841–4845. https://doi.org/10.26868/25222708.2019.211159

Doç, Y., Üniversitesi, S., Fakültesi, M., Mühendisliği, M., & Konya, B. (n.d.). *Ulaş Atmaca*.

Every, J. P., Li, L., & Dorrell, D. G. (2020). Köppen-Geiger climate classification adjustment of the BRL diffuse irradiation model for Australian locations. *Renewable Energy*, *147*, 2453–2469. https://doi.org/https://doi.org/10.1016/j.renene.2019.09.114

Gaygusuzoglu, G., & Bakis, A. (2017). The effect of material properties and isolation system on thermal bridge behavior. *Pamukkale University Journal of Engineering Sciences – Pamukkale Mühendislik Bilimleri Dergisi*, *23*(6), 687–693. https://doi.org/10.5505/pajes.2016.53496

Gutai, M., & Kheybari, A. G. (2020). Energy consumption of water-filled glass (WFG) hybrid building envelope. *Energy and Buildings*, *218*. https://doi.org/10.1016/j.enbuild.2020.110050

Indraganti, M., & Boussaa, D. (2017). A method to estimate the heating and cooling degree-days for different climatic zones of Saudi Arabia. *Building Services Engineering Research and Technology*, *38*(3), 327–350. https://doi.org/10.1177/0143624416681383

Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006). World map of the Köppen?Geiger climate classification updated. *Meteorologische Zeitschrift*, *15*(3), 259–263. https://doi.org/10.1127/0941?2948/2006/0130

Li, Y., Yin, W., Zhong, Y., Zhu, M., Hao, X., Li, Y., Ouyang, Y., & Han, J. (2023). Energy consumption of apartment conversion into passive houses in hot-summer and cold-winter regions of China. *Buildings*, *13*(1). https://doi.org/10.3390/buildings13010168

Ounis, S., Aste, N., Butera, F., Pero, C., Leonforte, F., & Adhikari, R. (2022). Optimal balance between heating, cooling and environmental impacts: A method for appropriate assessment of building envelope's U-value. *Energies*, *15*, 3570. https://doi.org/10.3390/en15103570

Schimschar, S., Boermans, T., Kretschmer, D., Offermann, M., & John, A. (2016a). *U-value maps Turkey Applying the comparative methodology framework for cost-optimality in the context of the EPBD Final report*. www.ecofys.com

Stevanović, S. (2013). Optimization of passive solar design strategies: A review. *Renewable & Sustainable Energy Reviews*, *25*, 177–196. https://api.semanticscholar.org/CorpusID:111235952

Süer, F. Z., & İlerisoy, Z. Y. (2022). Effects of exterior wall details and building locations on energy consumption of residential buildings in Turkey. *Gazi University Journal of Science Part B: Art Humanities Design and Planning*, *10*(2), 69–81.

Upcycling Practices in Construction: The Case of Sustainable Art House

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Abstract

Environmental concerns have continued to increase over the last decade due to the risks of resource scarcity and the Circular Economy (CE) concept has received attention since it provides a potential solution by re-using of materials in a closed loop. Upcycling, as a key component of the CE, aims to reduce the need for raw resources and drive the economic growth without waste generation. Construction industry is highly criticized in terms of resource consumption, waste generation, and carbon emissions; leading to a critical role to contribute to the Sustainable Development Goals, in particular Sustainable Cities and Communities. The main objective of this paper is to investigate the role of sustainable art in the regeneration of existing buildings. Within the context of this research, the Sustainable Art House is presented as an exemplary case that demonstrates an innovative approach towards the use of sustainable art concept. The study focuses on the investigation of the upcycling process based on the provided case study and discusses the main motivations as well as the resources and methods utilized, and the environmental, social, and economic sustainability-oriented benefits of this implementation. This study is expected to encourage the construction professionals to incorporate CE principles in their practices.

Keywords: *circular economy, construction industry, sustainability, upcycling, waste management.*

Introduction

Continuously growing global economy increases the demand for energy and materials as well as the waste generation and this results in a growing environmental concern (Bridgens et al., 2018). Currently, resource consumption in the World is not sustainable and has to change direction through a sustainable model. Eventually, inefficient consumption of non-renewable resources may result in a significant natural resource crisis (Hossain & Ng, 2018). Additionally, the growing climate crisis and global warming are the other consequences of the current global economy. All of these emerging problems are urging authorities to take action and develop new policies to shift the global economy to a more sustainable model (Przepiorkowska, 2020).

Linear economy (LE) model has been the basis of the global economy for a long time. In LE, products are manufactured from raw resources, consumed and finally classified as waste in a limited lifetime (EMF, 2015). On the other hand, this inefficient trend in LE is currently shifting through the Circular Economy (CE) model where products are used within a closed loop that enables resources to be utilized at their maximum value (Jacobsen, 2006). The CE model supports the use of renewable materials in a more efficient way that classifies waste as a resource and includes it into the closed loop of economy (Rahla et al., 2021). The new CE model for the global economy is regarded as the best sustainable development model (Le & Wu, 2010).

One of the key elements of the CE model is upcycling concept which aims to reduce the need for raw resources. It has been defined as valorization of waste materials into a value-added product (Yoon & Lee, 2024). Upcycling concept has been a part of humanity since ancient times as the pre-historic people crafted hand tools from bones (Bridgens et al., 2018). Upcycling can be driven by either survival needs or creation of an art craft (Bridgens et al., 2018) and both of these motivations serves for CE. Reuse of deconstructed materials can also be considered as a good example for upcycling and CE (Cimen, 2021).

Construction is a leading industry in terms of development of the global economy. As one of the largest production industries in Europe, it contributes almost 10% of the total GDP and creates more than 18 million jobs across Europe (CEN, 2017). On the other hand, the biggest consumer of non-renewable resources is the construction industry (Zimmann et al., 2016) and it is responsible for 40% of the total global waste by volume and 33% of human-caused global emissions (UNEP, 2012; WRI, 2016).

Since the consumption of the finite material resources is mostly driven by the construction industry (Krausmann et al., 2017), there is a huge opportunity to implement the CE model into construction processes. Within the literature, this emerging topic is mainly theoretical and there is a need for investigation of the real-world cases. For this reason, the research study showcases the Sustainable Art House as an exemplary case of upcycling application. The study aims to explore the upcycling process based on the motivational drivers as well as the strategies including utilized resources and methods, which consequently have implications on the environment, society, and economy in a positive manner.

Circular Economy in Construction

The concept of a CE related model first emerged in 1970s (Munaro et al., 2020) under the name of “Three R Principle” as reduce, reuse, recycle (Breteler, 2022). The term CE itself mentioned explicitly in 1988 by Allan Kneese (Kneese, 1988) and the CE concept has gained prominence in 1990s (EMF, 2015). In the meantime, the upcycling concept also originated in 1990s as reuse of discarded materials to create a product which has higher quality and value than the initial material (Wegener, 2016). Over the years, both terms have entered our lives more and more and started to be adopted by various industries. The construction industry has been considered as having the biggest potential for CE applications and adoption of eco-friendly technologies (Smol et al., 2015).

Within the literature, there is a consensus regarding the main strategies to enable a smooth transition of construction industry towards CE as reducing waste generation, facilitating resource recovery and extending building use (Hossain et al., 2020). Beside the strategies for adoption, there are vast number of research studies on the potential outcomes of the CE adoption within the construction industry. Akanbi et al. (2018) suggest that it is possible to enhance sustainability by using sustainable materials as the resource for production as a CE principle. In addition, Ghisellini et al. (2018) argue that recycling and reusing the materials in construction promotes efficiency in terms of CE. Hossain and Ng (2018) state that CE adoption reduces unnecessary waste generation.

On the other hand, some of the research in the literature proposed novel concepts, frameworks or roadmaps regarding the CE adoption in the construction industry. Yoon and Lee (2024) conducted a study and proposed a novel concept as waste upcycling-driven zero energy buildings which aims to foster the development of zero-energy buildings within the context of CE. Rahla et al. (2021) proposed a framework in order to investigate the strategies for implementation of CE throughout the building life cycle in different innovative aspects. Additionally, Mackenbah et al. (2020) conducted a study to develop a roadmap for the adoption of modular construction as a CE tool.

Moreover, some sort of research in the literature investigated the CE adoption in construction industry based on case studies. Scolaro and Medici (2021) presented a case study to show the use of downcycling and upcycling in rehabilitation of pre-existing buildings. Przepiorkowska (2020) conducted a research in order to support the CE approach in architecture and presented five case studies together with undertaken design methods, utilized materials and encountered CE processes. Although construction industry has a high potential for the adoption of CE strategies, real world applications are still at the infant stage and there are only few studies presents exemplary case studies.

Within the context of this research study, the Sustainable Art House has been investigated as an exemplary case of upcycling application. A basic framework is developed to represent the main motivations, utilized strategies and implications of the upcycling process in the case project. A structured interview has been held with the case project's representative to explore the reality based on the developed framework. The study is expected to encourage the construction professionals to incorporate CE principles in their practices.

Research Methodology

First of all, a comprehensive literature review has been conducted to explore the current trends and applications regarding CE and upcycling in the construction industry. Case study methodology is determined to be followed and a proper case is selected to investigate. In order to conduct a systematic investigation of the case project, a model framework has been developed based on a previous study by Ozorhon (2013). The developed framework represents the motivations, strategies, and implications of the upcycling process. A structured interview has been held with the creator of the Sustainable Art House and the real motivations, strategies and implications of the upcycling application are revealed.

Ozorhon (2013) has developed a framework in order to investigate the innovation process in the construction industry by defining innovation as a system with several components. The original framework has seven components from drivers and enablers to benefits and impacts in a three-dimensional representation. Following a simplification process, a conceptual framework composed of three components is developed as shown in Figure 1.

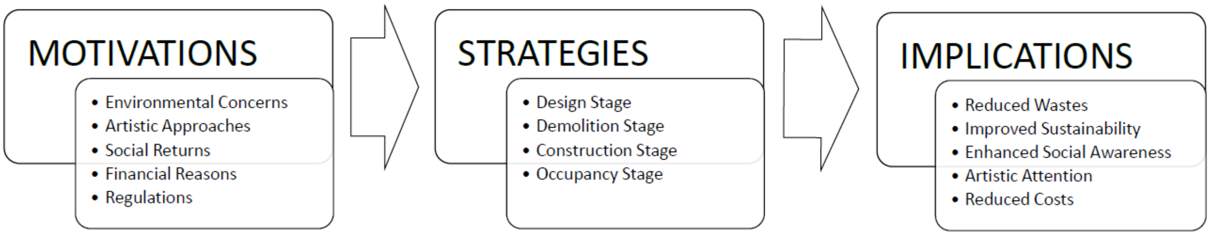

Figure 1: Developed framework to represent upcycling process.

The first component of the framework is motivations component which represents the main drivers behind the upcycling applications in the selected case project and consists of five sub categories. (i) Environmental Concerns (Rahla et al., 2021; Ting et al., 2023) that represents the desire to take an action against the adverse effects of global warming on the environment; (ii) Artistic Approaches category added since the case project is planned to be used as an art center; (iii) Social Returns (Scolaro & Medici, 2021) represent the positive effect of an upcycled building in terms of reputation and the perception of community; (iv) Financial Reasons (Cimen, 2021) are the expectation of a budget decrease thanks to the upcycling applications in the project; and finally (v) Regulations (Ting et al., 2023) which basically represents global actions to reach previously set targets.

Secondly, as the core component of the framework, strategies cluster represents all of the utilized methods and applied strategies to achieve the upcycling process in different stages of the building life-cycle. The initial stage is the (i) Design Stage that is very significant for planning the upcycling strategies for material selection. (ii) Demolition Stage is critical to classify the wastes which will be upcycled and become a part of the project in the future. (iii) Construction Stage is where most of the planned strategies are utilized and (iv) Occupation Stage represents the strategies that are utilized during usage of the building.

As the final component of the model framework, implications cluster represents the impacts of upcycling process in the case project and it includes five sub categories. (i) Reduced Wastes (Hossain et al., 2020) is an expected consequence of upcycling thanks to reusage of various materials. (ii) Improved Sustainability (Mackenbah et al., 2020) is another implication of upcycling applications; (iii) Enhanced Social Awareness (Guerra & Leite, 2021; Scolaro & Medici, 2021) due to the project's positive impact on the society; (iv) Artistic Attention has been added since the case project is an art house and recycling is a basic concept that the artist used in her creations; and finally (v) Reduced Costs (Ting et al., 2023) are expected because a lot of existing component of the building is upcycled instead of buying new ones.

Case study methodology has been employed as the principal research method in this study. The case study is a research strategy covering the logic of design, data collection techniques and specific approaches to data analysis (Yin, 2003). In this context, the case study is neither a data collection method nor a design feature alone (Stoecker, 1991) but a comprehensive research strategy. A comprehensive definition of case study methodology made by Schramm (1971, cited in Yin 1989: 22-23) as, "The essence of a case study, the central tendency among all types of case, is that it tries to illuminate a decision or set of decisions: why they were taken, how they were implemented and with what result". When a research asks who and where questions, it usually supports survey methods whereas how and why questions are more explanatory and usually used in histories, experiments and also case studies to present background information in detail.

Since the answers of questions how and why are sought in this research, case study is determined as the principal research methodology to be implemented in this study. A proper case project for this study should be a good example for upcycling practices in the construction industry which utilized several strategies to implement CE and upcycling in several stages of the building life cycle. In addition, the selected case project should be able to provide necessary information for the research and the representative should be eager to be a part of the research. In this context, the Sustainable Art House of Deniz Sagdic has been selected to investigate the upcycling process.

The Sustainable Art House is an upcycled art center located in Ataşehir district of İstanbul with a total construction area of 600 sqm. The project is based on transforming a 2-storey existing building built in 1970s in line with the targets and needs of the owner. A sustainability-based approach is adopted for the transformation process and upcycling practices were implemented. The project provides good examples for circularity, sustainability, lean construction and supply chain management.

Upcycling Processes & Sustainability

In-depth information has been gathered based on a structured interview held with the creator of the Sustainable Art House and written contributions of two architects who managed the process thoroughly. Motivations, strategies and implications of the upcycling process in the case project were discussed based on real examples and the interview has been recorded and analyzed based on the notes taken during the discussion. According to Deniz Sagdic, creator of the Sustainable Art House, the motto of the case project was "*Every waste constitutes a raw material*."

In the Sustainable Art House, the main motivation behind the upcycling applications was the environmental concerns to create a sustainable world for future generations. This was targeted to be achieved by reducing total carbon footprint through the reuse of waste materials and by lowering the energy consumption. The project was designed with this strong motivation starting from the initial stages.

Creator of the Sustainable Art House is a professional artist who adopted the upcycling concept in her works and created various pieces of art by adding value to waste materials. In line with her artistic approaches, another motivation behind the Sustainable Art House is to create a living masterpiece that lasts forever and became a functional and sustainable museum that represents the artist's upcycling approach.

Social returns, as a motivation, in terms of changing the perception of society was an initial target of the project. Proving that it is possible to build a building that only meets our needs and is compatible with environmental concerns will give the desired message to the society. Regardless of reputational gains, this project is hoped to set an example for many upcycling applications in the future.

When it comes to financial motivations, it is noted that although financial gains were expected thanks to upcycling strategies to be utilized, it was not among the main sources of motivations in this project. Finally, regulations and global targets to popularize CE can be a direct source of motivation when it become localized.

Table 1. Upcycling strategies by project phases.

Phase	Upcycling Strategies
Design Stage	Specific selection criteria
	Energy efficient design approach
	Sustainable material selection
Demolition Stage	Renovation instead of demolition
	Reduced waste creation
	Reuse of waste materials
Construction Stage	Sustainable reinforcement
	Locally obtained waste materials
	Green terrace applications
Occupation Stage	Solar energy panels
	Rain water harvesting
	Sustainable occupation

Utilized upcycling strategies have been classified according to different phases of the case project as design stage, demolition stage, construction stage, occupation stage. Details are given in Table-1 above.

First of all, main selections were made to suit the upcycling purpose of the project and an old two-storey building was purchased in an area where there were no high-rise buildings. Although the local laws permit for new four-storey building, the existing building was kept as two storeys according to the project's needs and renovated instead of demolishing. Additionally, design approach of the building was based on passive design strategies. For example, windows' locations were decided according to the sun's positions and insulation applications were done to lower the building's water and energy demand. As a last item for the design stage, sustainability and upcycling were considered for the material selection. Recyclable aluminum materials were preferred for windows' frames instead of plastic and timber was not chosen in order not to harm any trees.

In contrast to its name, almost no demolition was held during the demolition stage and the old building is completely renovated in line with the upcycling targets. In order to reduce the waste creation, minimum changes made on the building layout and almost all components of the old building were utilized. As an example, for reusing the waste materials, the resulting rubble was turned into sand and used as raw material in the plastering processes to be carried out in the building. In this respect, upcycling practices supports the concept of lean construction by eliminating wastes and simplifying processes.

Figure 2: Existing and final versions of the building.

During the construction stage, it has been found out that the old building had an inadequate foundation and a statically inadequate structure. A foundation has been constructed from scratch while the existing building remains in place and the structural reinforcements were done by using steel which is erectable and convenient for future upcycling applications. When it comes to façade and exterior walls surrounding the land, leftover scrap sheet materials were obtained from a local factory and upcycled as the main component of the façade and exterior walls. This application is also a good example as a supply chain management activity. Additionally, the old building's roof was turned to a green terrace that is convenient for agricultural activities.

Finally, there were three main strategies applied for the occupation stage. The case project has a solar energy system that is installed to produce electricity. System works with a 130% efficiency during summer times and the extra energy is sold to the main electricity agency. Additionally, there is a rainwater harvesting system which is connected to a 2 tons of water tank with a water purifier. The building is occupied with two different purposes first as an art center and second as a home for the creator. In this way, the need for transportation is eliminated which consequently reduces the carbon foot print of the building user.

Figure 3: Solar energy panels & sustainable terrace.

As a result of the process, there are various implications both for the project and the society. First of all, the total wastes to be created due to the construction of the Sustainable Art House is reduced. The project is improved in terms of sustainability and the Art House became a self-sufficient structure. Additionally, for certain activities, where upcycling strategies applied, the construction cost is reduced. However, due to currency fluctuations and unexpected project specific problems such as foundation reinforcement, the total cost of the project is increased from the initial budget.

The project enhanced social awareness regarding CE activities, sustainability, and upcycling. During the interview, it has been stated that schools and universities are organizing educational trips to the Sustainable Art House to see the examples in place. The project also attracts an artistic attention all around the World. Both local and international tourist groups visit the art house as a museum.

In the final part of the interview, the challenges encountered during the upcycling process have brought up. The biggest challenge was the people's resistance to change. Since the upcycling approach requires non-standard applications, it was hard to describe the intended final product and how it should have been done. Additionally, bureaucratic procedures such as obtaining permits and project specific problems such as barriers due to the existing building's conditions were the other challenges encountered.

Conclusion

Over the few decades, the growing environmental concerns due to the climate crisis and resource scarcity put a significant responsibility on the construction industry. As one of the largest industries in the World, construction industry and the built environment plays an important role in unsustainable resource consumption. Emergence of CE showed that there is a huge opportunity to apply CE principles in the construction. Upcycling, as an important component of the CE, is the key to reduce the need for raw resources and drive the economic growth without harming the environment. This study investigated the upcycling process in the Sustainable Art House as a case study and revealed the main motivations, strategies, and implications of the application.

The upcycling process in the Sustainable Art House provides good examples for the future applications in the construction industry. The main motivations show where authorities should focus to increase the upcycling adoption. Promoting both environmental and financial benefits of adopting CE principles will increase the industrial awareness. Moreover, producing industry standards and regulations as well as offering incentives are also expected to increase the upcycling and CE adoption.

Utilized strategies show that upcycling is an approach which grows in a combination with sustainable practices in construction. A detailed plan should be made for every single project by evaluating the project-specific situations and the strategies to be utilized in line with this plan should be determined. In renovation projects, conditions of the existing building are curial and readily available old materials should be evaluated carefully for identifying the upcycling opportunities. CE approach in the Sustainable Art House provides a good example for not only the upcycling practices but also for green buildings, lean construction, and supply chain management concepts.

From a wider perspective, renovation of existing buildings through upcycling approach is the key for urban regeneration in metropolitan cities. Traditional economy approach is based on demolishing large areas, by creating lots of wastes, and developing huge multi-purpose projects, by consuming lots of resources. Whereas CE approach supports upcycling of existing buildings separately in single small areas by preserving the texture and culture of the provinces as well as the environment and the raw resources. In this study, the Sustainable Art House is presented as an exemplary case and expected to encourage the construction professionals to incorporate CE principles in their practices.

References

Akanbi, L. A., Oyedele, L. O., Akinade, O. O., Ajayi, A. O., Delgado, M. D., Bilal, M., & Bello, S. A. (2018). Salvaging building materials in a circular economy: a BIM-based whole-life performance estimator. *Resources Conservation Recycling*, 129.

Breteler, F. H. R. (2022). Enhancement of the process of reusing building products.

Bridgens, B., Powell, M., Farmer, G., Walsh, C., Reed, E., Royapoor, M., Gosling, P., Hall, J., & Heidrich, O. (2018). Creative upcycling: Reconnecting people, materials and place through making. *Journal of Cleaner Production*, 189, 145-154.

Cimen, O. (2021). Construction and built environment in circular economy: A comprehensive literature review. *Journal of Cleaner Production*, 305.

Ellen MacArthur Foundation (EMF). (2015). Growth within: a Circular Economy Vision for a Competitive Europe. Ellen MacArthur Foundation. www.ellenmacarthurfoundation.org/assets/downloads/publications/EllenMacArthurFoundation_Growth-Within_July15.pdf.

Ellen MacArthur Foundation (EMF). 2015. Growth within: a Circular Economy Vision for a Competitive Europe.

European Committee for Standardization (CEN). (2017). CEN/TC 442 Business Plan. Building information modelling (BIM). www.standards.cen.eu/BP/1991542.pdf.

Ghisellini, P., Ripa, M., & Ulgiati, S. (2018). Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review. *Journal of Cleaner Production*, 178.

Guerra, B. C., & Leite, F. (2021). Circular economy in the construction industry: An overview of United States stakeholders' awareness, major challenges, and enablers. *Resources, Conservation and Recycling*, 170.

Hossain, M. U., & Ng, S. T. (2018). Critical consideration of buildings' environmental impact assessment towards adoption of circular economy: An analytical review. *Journal of Cleaner Production*, 205, 763–780.

Hossain, M.U., Ng, S.T., Antwi-Afari, P., & Amor, B. (2020). Circular economy and the construction industry: existing trends, challenges and prospective framework for sustainable construction. *Renewable and Sustainable Energy Reviews*, 130.

Jacobsen, N.B. (2006). Industrial symbiosis in kalundborg, Denmark: a quantitative assessment of economic and environmental aspects. *Journal of Industrial Ecology*, 10, 239-255.

Kneese, A. V. (1988). The Economics of Natural Resources. *Population and Development Review*, 14, 281–309.

Krausmann, F., Wiedenhofer, D., Lauk, C., Haas, W., Tanikawa, H., Fishman, T., Miatto, A., Schandl, H., & Haberl, H. (2017). Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. *Proceedings of the National Academy of Sciences* U.S.A., 114 (8), 1880–1885.

Le, W. & Wu, C. (2010). Construction of coal eco-industrial park based on the theory of circular economy. 2010 *International Conference on E-Product E-Service and E-Entertainment (ICEEE 2010)*, 1-3.

Mackenbach, S., Zeller, J., & Osebold, R. (2020). A Roadmap towards Circularity - Modular Construction as a Tool for Circular Economy in the Built Environment. *IOP Conference Series Earth and Environmental Science*. 588.

Munaro, M. R., Tavares, S. F., & Braganca L. (2020). Towards circular and more sustainable buildings: A systematic literature review on the circular economy in the built environment, *Journal of Cleaner Production*, 260.

Ozorhon, B. (2013). Analysis of construction innovation process at project level. *Journal of Management in Engineering*, 29(4), 455-463.

Przepiorkowska, S. (2020). The Circular Economy approach in architecture – a study of 5 bottom-up cases. *Builder*, 279, 33-39.

Rahla, K. M., Mateus, R., & Bragança, L. (2021). Implementing circular economy strategies in buildings—from theory to practice. *Applied System Innovation*, 4(2), 26.

Scolaro, A. M.; De Medici, S. (2021). Downcycling and Upcycling in Rehabilitation and Adaptive Reuse of Pre-Existing Buildings: Re-Designing Technological Performances in an Environmental Perspective. *Energies*, 14.

Smol, M., Kulczycka, J., Henclik, A., Gorazda, K., & Wzorek, Z. (2015). The possible use of sewage sludge ash (SSA) in the construction industry as a way towards a circular economy. *Journal of Cleaner Production*, 95, 45-54.

Ting, L. S., Zailani, S., Sidek, N. Z. M., & Shaharudin, M. R. (2023). Motivators and barriers of circular economy business model adoption and its impact on sustainable production in Malaysia. *Environment, Development and Sustainability*, 1-28.

United Nations Environment Programme. (2012*). Sustainable, resource efficient cities – making it happen!* Paris.

Wegener, C. (2016). Upcycling, Creativityda New Vocabulary. Springer, 181-188.

World Resources Institute (WIR). (2016). Accelerating building efficiency: eight actions for urban leaders. www.wri.org/publication/accelerating-building-efficiency-actions-city-leaders

Yoon, S., & Lee, J. (2024). Perspective for waste upcycling-driven zero energy buildings, *Energy*, 289.

Zimmann, R., O'Brien, H., Hargrave, J., & Morrell, M. (2016). *The Circular Economy in the Built Environment*. Arup, London.

Life Cycle and Life Cycle Cost Assessment of Solid vs. Hollow Concrete Masonry Blocks

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Abstract

Building materials influence environmental footprint and economic costs in construction projects. Concrete masonry blocks are bulk construction material that also create considerable environmental impact and costs. This study conducted Life Cycle Assessment (LCA) and Life Cycle Cost Assessment (LCCA) to compare the environmental and economic impacts of hollow versus solid concrete masonry blocks. LCA was conducted through framework based on ISO 14040 and ISO 14044 standards and utilizing building energy modelling and simulation for operational phase. LCCA was performed using Equivalent uniform annual cost (EUAC) calculation. The comparison between environmental impacts of manufacturing 1,000 solid and hollow blocks reveals that solid blocks produce marginally higher CO_2 emissions at 720.01 kg compared to 712.86 kg for hollow blocks. While for operational energy use all emission types (CO_2, NO_x, CH_4) are less in case of hollow blocks than solid blocks for a year of energy use. LCCA results show that Hollow blocks had lower manufacturing EUAC at Rs 28.66 each ($0.1), against Rs 32.78 ($0.12) for Solid blocks. Moreover, solid blocks incur a higher annual operational cost per block, at Rs. 70.33 ($0.25), compared to PKR 56.26 ($0.2) for hollow blocks. Hence, hollow blocks are sustainable and economically viable option for construction.

Keywords: *energy efficiency, hollow concrete blocks, life cycle assessment (LCA), life cycle cost assessment (LCCA), sustainable construction.*

Introduction

The construction industry is one of the significant contributor to global greenhouse gas (GHG) emissions, resource depletion, and environmental degradation (Nadzirah & Dhuny Bibi Fatimah, 2020). Increasing demand for building and infrastructure development exacerbates these environmental challenges stressing the importance of sustainable practices (Dsilva et al., 2023). Selection of building materials is significant decision that influences ecological footprint and financial costs of construction projects (Rahla et al., 2021). Concrete masonry blocks are the most used bulk construction material (Parsekian et al., 2019). Therefore, these also generate considerable environmental impacts (Rahla et al., 2021), as well as incur significant costs. Life Cycle Assessment (LCA) and Life Cycle Cost Assessment (LCCA) are decision-making tools that can be used to accurately determine sustainability impacts of different material alternatives.

This study aims to provide an assessment framework and compare solid and hollow concrete blocks using LCA alongside operational energy analysis, and LCCA. It seeks to guide the choice of more environmentally and economically sustainable block.

Objective, Scope, and Methodology

The *objective* of this study was to assess sustainability of solid and hollow concrete masonry blocks by evaluating their life cycle environmental impacts, energy efficiency, and life cycle costs. The *scope* includes assessing LCA from cradle to gate plus operational energy efficiency during use of blocks in a house. LCCA scope includes construction expenses, ongoing maintenance, and operational energy consumption.

The *methodology* includes literature review that resulted in developing understating, assessment framework (based on ISO Standards), an extraction of secondary data required for LCA and LCCA of solid and hollow concrete blocks. It proceeds with gathering cradle-to-gate data, including raw material sourcing and manufacturing emissions. An operational energy analysis using Building Information Modelling (BIM) through AutoDesk Revit and Insight 360, was performed to assesses building energy efficiency. Thereafter, LCCA was performed by calculating, Equivalent Uniform Annual Cost (EUAC) to compare economic implications. Conclusions and recommendations have been drawn.

Literature Review

The environmental impacts of construction materials, particularly concrete, have been extensively documented. The production process of concrete not only depletes natural resources but also have environmental impacts such as; global warming (Kim et al., 2016). Cement production has been identified as key source of carbon footprint generation. However, impacts of traditional concrete block production had also been emphasised by researchers as another significant contributor (Rahla et al., 2021; van Oss & Padovani, 2003). Alternative materials like hollow concrete blocks can help reducing these impacts, in alignment with broader goal of sustainable construction (Al-Tarbi et al., 2022). The comparative assessment for sustainability dimensions including; environment and cost can help ascertain this claim. LCA is a systematic approach for assessing the environmental impacts of building materials across their entire lifecycle—from extraction and manufacturing to usage and disposal (Ghanbari, 2023). This method allows for a holistic understanding of the environmental consequences of choosing any construction material The operational energy analysis further examines the energy consumption patterns of buildings constructed with these materials, providing insights into their efficiency and potential for energy cost savings over time (Ghanbari, 2023). LCCA can provide economics' perspective on long-term costs associated with each type of block (Vasishta et al., 2023). This can be done by evaluating initial investment, maintenance, operation, and disposal costs. LCCA enables a comprehensive assessment of the economic viability of the construction materials.

Life Cycle Assessment

In this study, the Life Cycle Assessment (LCA) was conducted through assessment framework defined in accordance with the ISO 14040 and ISO 14044 standards. The conceptual method of the same is illustrated through Figure 1. The focus was on the environmental impacts associated with the production of solid and hollow concrete masonry blocks. Additionally, operational energy analysis was performed using thermal properties of both block types through Building Information Modeling and Energy Simulation for a typical house. The objective is to compare the environmental impacts of solid and masonry concrete blocks production, adopting a cradle-to-gate plus operational energy use impact.

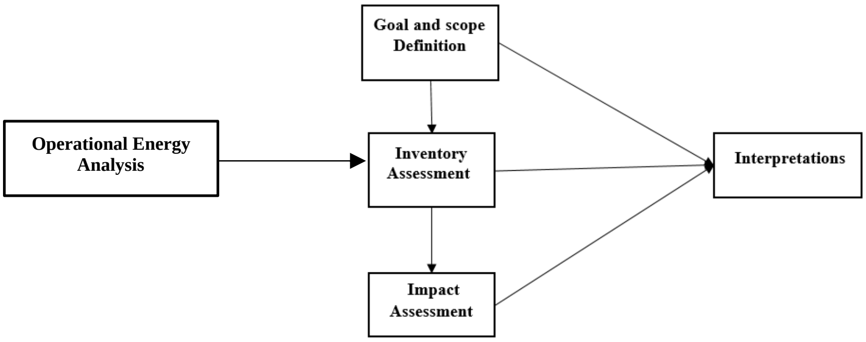

Figure 1: Life cycle assessment methodology.

Manufacturing Phase – Cradle-to-Gate Analysis

The analysis covered impacts from raw material extraction to the manufacturing facility exit, with the functional unit defined as the impact per 1,000 blocks to ensure comparability. Figure 2 shows the process flowchart illustrating process, material, resource inputs as well as system boundaries considered for analysis.

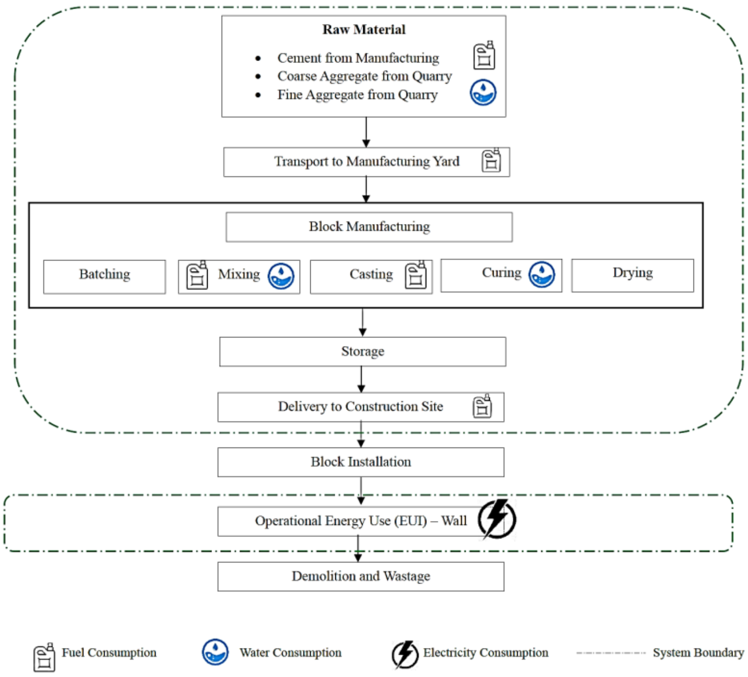

Figure 2: Block manufacturing process - LCA process flow chart.

For inventory assessment and development, primary data were collected through field visits to manufacturing two sites as illustrated in Figure 3. The LCA material input data as collected from the sites is provided in Table 1.


(a)


(b)

Figure 3: Site Visit (a) solid block manufacturing yard (b) hollow blocks manufacturing yard.

Table 1. Life cycle inventory - material input.

Inputs			
Description	Unit	Solid Block	Hollow Blocks
Cement Consumed	Kg/ 1000 blocks	750.00	750
Coarse Aggregates extraction	Kg/ 1000 blocks	2654.7	5309.4
Fine Aggregates extraction	Kg/ 1000 blocks	8760.51	5840.34
Aggregates transportation Fuel	L/1000 Blocks	27.03	2.65
Cement Transportation Fuel	L/1000 Blocks	8.59	6.72
Water consumption	L/1000 Blocks	250	250
Electricity consumed	KWH/1000 Blocks	0.00	0.00
Batching Fuel	L/1000 Blocks	2.69	3
Casting fuel	L/1000 Blocks	0.1	0.00
Curing Water Electricity consumption	KWH/1000 Blocks	0.00	0.00
Energy Consumed in Cement Production	MJ/Kg	4-7	4-7
Delivery Fuel Consumption (For 25Km round trip)	L/1000 Blocks	0.00	16.67
Total Transportation Fuel	L/1000 Blocks	35.63	26.04

Emission factors for different types of emissions were collected utilizing secondary data from literature and databases. The focus was on emission factors related to production processes, energy consumption, and transportation. Table 2 provides emission factors and identifies sources.

Table 2. Emissions factors.

Emission Source/Type	CO_2	NOx	SOx	CH_4	CO	N_2O	Source
Cement (g/Kg)	861.2	2.279	3.646	1.002	4.203	0.0007	(Marinković, 2013)
Mix Aggregates (g/Kg)	1.377	0.015	0.005	0.001	0.003	0.00006	(W J Luo)
Electricity (g/KWH)	516.375	0.003	0	0.017	0	0	(Khan, 2017)
Casting Petrol (g/L)	1053.444	0	0	0	0	0	(Kaleem Anwar Mir 2016)
Batching Diesel (g/L)	999.163	2.708	2.091	0.045	0.18	0.009	

Two key equations were used to calculate environmental impact of producing 1,000 concrete blocks

General Emissions: $\sum \text{Emission} = \sum(\text{Material Input x Emission Factor})$ (1)

CO_2 Emissions: $\sum CO_2\ Emissions = (Cement\ consumed\ x\ EF\ Cement) + (Aggregate\ Consumed\ x\ EF\ Aggregate)$ …. (2)

Field data and emission factors were used in these equations to assess environmental impacts. The emission results are provided in Table 3.

Table 1. Life cycle inventory - material output.

Outputs			
Description	Unit	Solid Blocks	Hollow Blocks
CO_2 Emission	kg/1000 blocks	720.01	712.86
NO_x Emission	kg/1000 blocks	1.85	1.88
SO_x Emission	kg/1000 blocks	2.83	2.83
CH_4 Emission	kg/1000 blocks	0.76	0.76
CO Emission	kg/1000 blocks	3.17	3.18
N_2O Emission	kg/1000 blocks	0	1.15E-03
HCl Emission	kg/1000 blocks	0.05	5.09E-02
HC Emission	kg/1000 blocks	0	4.35E-04
NMVOC Emission	kg/1000 blocks	0.03	3.27E-02
Particulate Matter	kg/1000 blocks	0.54	0.54
Cement Bags	Bags paper recycled		
Waste Generated	g/1000 blocks	0	0

The comparison between environmental impacts of manufacturing 1,000 solid and hollow blocks reveals that solid blocks produce marginally higher CO_2 emissions at 720.01 kg compared to 712.86 kg for hollow blocks, indicating a slight environmental advantage for hollow blocks. However, hollow blocks have slightly elevated NOx emissions. Emissions such as SOx, CH_4, CO, and particulate matter are comparatively similar for both block types.

although present in minimal quantities. These differences inform the environmental impact assessment, with hollow blocks showing a potential for reduced emissions, depicted in Figure 5.

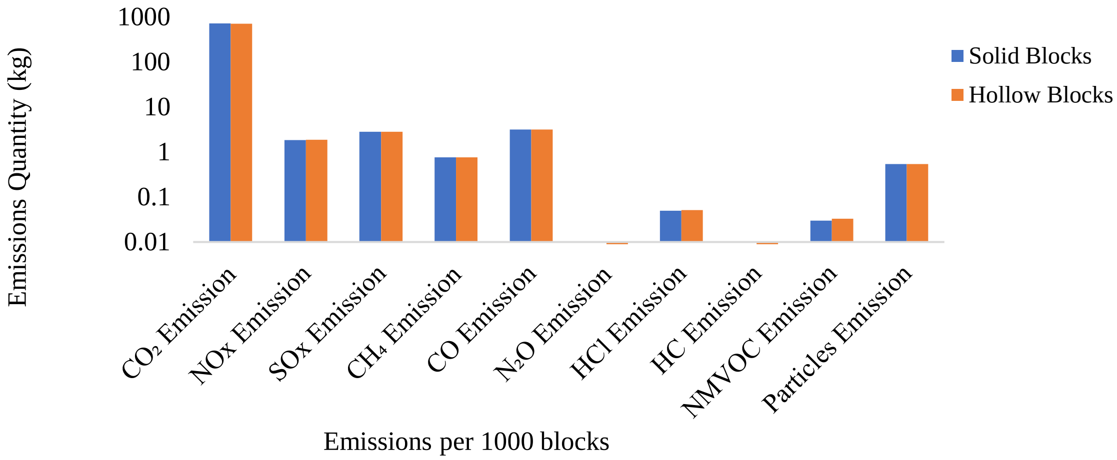

Figure 4: Solid and hollow blocks emissions.

Operational Energy Use - Energy Analysis

An operational energy analysis was conducted for a residential house of 120 sq/yd, evaluating two constructions: one with solid blocks and another with hollow blocks, to determine their Energy Use Intensity (EUI). Utilizing Autodesk Revit, accurate energy models for both constructions were developed, incorporating building specifications, materials, occupancy, and specific thermal properties for solid and hollow blocks. These models were further analyzed in Insight 360, providing advanced tools for energy evaluation as seen in Figure 4.

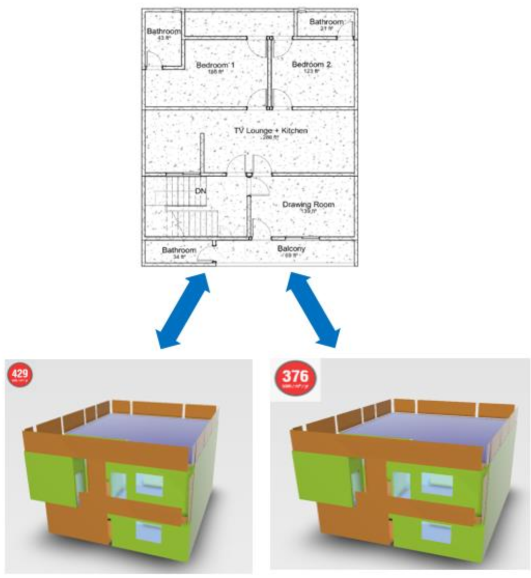

Figure 5: (a) Architectural plan of the residential house. (b) energy model of the residential house constructed with solid blocks, EUI of 429. (c) 3D energy model of the residential house constructed with hollow blocks, EUI of 376.

The analysis was performed for analysis unit of 1000 blocks after finding out EUI for the same using the EUI for actual blocks used. The results of solid and hollow blocks underscore the efficiency of hollow blocks, depicted in Table 4. Specifically, a structure using solid blocks shows a higher Energy Use Intensity (EUI) of 429 KWh/m^2/year versus 376 KWh/m^2/year for one with hollow blocks, even with identical wall areas. This significant EUI difference means the hollow blocks house benefits from a notably lower annual energy footprint. The emission factors were taken from Table 2 for electricity. Results show that all emission types (CO_2, NO_x, CH_4) are less in case of hollow blocks than solid blocks for a year of energy use.

Table 2. EUI and emissions of solid and hollow blocks.

Information	Units	Solid Block House	Hollow Blocks House
EUI	KWH/sq.m/year	429.0	376.0
Walls Area	sq.m	514.9	514.9
EUI (For 7723 Blocks/actual)	KWH/year	220874.9	193587.4
EUI (For 1000 Blocks/analysis unit)	KWH/year	28599.6	25066.3
CO_2 Emission	Kg	14768.134	12,943.6
NO_x Emission	Kg	0.090	0.079
CH_4 Emission	Kg	0.514	0.451

Life Cycle Cost Assessment

Equivalent Uniform Annual Cost (EUAC) was used to evaluate the LCCA associated with solid and hollow block manufacturing and energy use. EUAC provides annualized cost equivalent over the life cycle of an asset, considering the time value of money by discounting future costs and revenues to their present values, this method is utilized to examine the entre life cycle cost of solid and hollow blocks.

$$EUAC = P\left(\frac{A}{P,i,n}\right) + Ad + Am + Ao \quad (3)$$

P = Present cost (Rs), A_m = Annual maintenance cost (Rs), A_o = Annual operational cost (Rs), A_d = Annual equipment depreciation cost (Rs), I = Interest rate (%), n = Number of years

Manufacturing LCCA

The results of analysis are shown in Table 5. Equivalent Uniform Annual Cost (EUAC) per block of hollow blocks was found better than that of solid. Hollow blocks had lower manufacturing EUAC at Rs 28.66 each ($0.1), against Rs 32.78 ($0.12) for Solid blocks.

Table 3. EUAC for solid and hollow blocks.

Quantity	Solid Blocks	Hollow Blocks
Material cost per block	**Rs 32.41**	**Rs 28.64**
No. of blocks manufactured per day	1300	19000
No. of blocks manufactured per year	474500	6935000
Useful life of plant and equipment (years)	10	10
Interest rate (SBP)	22%	22%
1st year equip. depreciation expense	Rs 155,454.6	Rs 155,454.6
Equip. depreciation gradient G(A/G, i, n)	Rs 64,927.25	Rs 64,927.25
Equip. depreciation to annuity	Rs 90,527.3	Rs 90,527.3
Equip. depreciation expense per block	**Rs 0.19**	**Rs 0.01**
Plant annual maintenance cost	Rs 84,000.00	Rs 84,000.00
Plant annual maintenance cost per block	**Rs 0.18**	**Rs 0.01**
Total Manufacturing Cost (EUAC)/block	**Rs. 32.78**	**Rs. 28.66**

Operational Energy LCCA

The operational cost per year per block for solid and hollow blocks are shown in Table 6. These were calculated based on Cost EUI by dividing the operational cost per year of blocks with total number of blocks used in a house. Operational cost per year per block for solid and hollow blocks of each residential unit (120 sq. yds) is depicted in Table 6. Solid blocks incur a higher annual operational cost per block, at Rs. 70.33 ($0.25), compared to PKR 56.26 ($0.2) for hollow blocks.

Table 4. Operational cost per year per block of solid and hollow blocks.

House Block Type	EUI Overall Cost (USD/sqm/yr)	EUI Cost Wall (USD/sqm/yr)	Conversion Rate	EUI Cost (PKR/Yr)	Wall Area - sq. m	Operational cost(PKR/Yr)	No of Blocks In Residential Unit	Operational PKR/Yr/Block
Solid	43.70	3.65	289	1,054.85	514.9	543,142.27	7723	70.33
Hollow	40.80	2.92	289	843.88	514.9	434,513.81	7723	56.26

Conclusions and Recommendations

The study provides a comprehensive comparison between solid and hollow concrete blocks through Life Cycle Assessment (LCA) and Life Cycle Cost Assessment (LCCA), revealing that hollow blocks not only minimize environmental impacts but also enhance energy efficiency and offer considerable cost savings over their lifecycle. By examining the operational energy analysis and operational costs, the findings underscore the economic and environmental benefits of adopting hollow blocks in construction. This research advocates for their use as a sustainable and economically viable option, contributing to the advancement of sustainable construction practices.

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References

Al-Tarbi, S. M., Baghabra Al-Amoudi, O. S., Al-Osta, M. A., Al-Awsh, W. A., Ali, M. R., & Maslehuddin, M. (2022). Development of eco-friendly hollow concrete blocks in the field using wasted high-density polyethylene, low-density polyethylene, and crumb tire rubber. *Journal of Materials Research and Technology*, *21*, 1915-1932.

Dsilva, J., Zarmukhambetova, S., & Locke, J. (2023). Assessment of building materials in the construction sector: A case study using life cycle assessment approach to achieve the circular economy. *Heliyon*, *9*(10), e20404.

Ghanbari, M. (2023). Environmental Impact Assessment of Building Materials Using Life Cycle Assessment. *Journal of Architectural Environment & Structural Engineering Research*, *6*, 11-22.

Kaleem Anwar Mir , M. I. (2016). *Greenhouse Gas Emission Inventory of Pakistan for the Year 2011-2012*.

Khan, W. M., 2, S. Siddiqui. (2017). Estimation of Greenhouse Gas Emissions by Household Energy Consumption: A Case Study of Lahore, Pakistan. *Pakistan Journal of Meteorology*, *14*(27).

Kim, T., Tae, S., & Chae, C. U. (2016). Analysis of Environmental Impact for Concrete Using LCA by Varying the Recycling Components, the Compressive Strength and the Admixture Material Mixing. *Sustainability*, *8*(4).

Marinković, S. B. (2013). 3 - Life cycle assessment (LCA) aspects of concrete. In F. Pacheco-Torgal, S. Jalali, J. Labrincha, & V. M. John (Eds.), *Eco-Efficient Concrete* (pp. 45-80). Woodhead Publishing. https://doi.org/https://doi.org/10.1533/9780857098993.1.45

Nadzirah, Z., & Dhuny Bibi Fatimah, Z. (2020, 2020/12/30). Factors Contributing to Carbon Emission in Construction Activity. Proceedings of the Third International Conference on Separation Technology 2020 (ICoST 2020),

Parsekian, G., Roman, H. R., Silva, C. O., & Faria, M. S. (2019). 2 - Concrete block. In B. Ghiassi & P. B. Lourenço (Eds.), *Long-term Performance and Durability of Masonry Structures* (pp. 21-57). Woodhead Publishing. https://doi.org/https://doi.org/10.1016/B978-0-08-102110-1.00002-9

Rahla, K. M., Mateus, R., & Bragança, L. (2021). Selection Criteria for Building Materials and Components in Line with the Circular Economy Principles in the Built Environment—A Review of Current Trends. *Infrastructures, 6*(4).

van Oss, H. G., & Padovani, A. C. (2003). Cement Manufacture and the Environment Part II: Environmental Challenges and Opportunities. *Journal of Industrial Ecology*, *7*(1), 93-126.

Vasishta, T., Hashem Mehany, M., & Killingsworth, J. (2023). Comparative life cycle assesment (LCA) and life cycle cost analysis (LCCA) of precast and cast–in–place buildings in United States. *Journal of Building Engineering*, *67*, 105921.

W J Luo, X. C. M., C Y Meng, L J Xu, J Y Tsou, S L Yang and Z C Mao. Carbon emission modeling and analysis of building materialization process. *IOP Conference Series: Earth and Environmental Science, Volume 531, 2020 3rd International Conference of Green Buildings and Environmental Management 5-7 June 2020, Qingdao, China*.

Conceptual Design of Energy Efficient Housing Unit in Hot & Humid Urban Areas

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Abstract

Buildings, especially residential buildings, contributes significantly to the total energy consumption of a country. To address immediate energy concerns, this paper proposes a conceptual design for energy efficient buildings. These design related improvements and diverse energy-efficiency techniques can be incorporated in existing structures and new residential buildings to enhance the energy efficiency of the buildings. The focus of the improvements is hot and humid climate zones where the majority of energy is consumed in cooling the buildings.

Drawing upon a comprehensive review of international construction practices, this paper contrasts foreign methodologies with local approaches, emphasizing effective strategies implemented by architects and contractors.

By amalgamating active and passive strategies, this research contributes a conceptual blueprint for an energy-efficient urban building. The proposed blueprint aligns with global, national, and local standards, offering tailored suggestions and solutions to elevate energy conservation in buildings.

Keywords: *building design, energy efficiency, residential*

Introduction

The escalating demand for energy in residential constructions is a critical global concern, underscored by the International Energy Agency's (IEA) data showing a persistent increase in global building energy consumption. In 2022, the buildings sector saw a 1% rise in energy consumption, with operational energy use representing approximately 30% of global final energy consumption, a figure that climbs to 34% when considering energy used in producing essential building materials like cement, steel, and aluminum (IEA, 2023).

Recognizing the pivotal role of buildings in global energy consumption and its consequential environmental impact, there's an urgent need for innovative energy-saving measures, particularly in regions prone to hot and humid climates. Since as per the latest statistics, in 2022, space cooling demand surged by over 3%, while space heating decreased by 4%, signaling the need for tailored solutions for hotter climatic conditions (IEA, 2023).

This paper addresses these challenges by proposing a conceptual design for energy-efficient residential units specifically suited for hot and humid climates. Drawing upon recent advancements in the field, the proposed design aims to mitigate energy consumption while ensuring optimal comfort and livability for occupants, contributing to sustainable development efforts (IEA, 2023).

Literature Review

In conducting the literature study, a systematic approach was employed to gather relevant information from various scholarly sources, including journal publications, international best practices, codes, specifications, and reputable online databases. The search strategy involved keyword searches, citation tracking, and examination of relevant literature within the field of energy-efficient building design, focusing specifically on hot and humid climatic regions. The literature review process encompassed the identification of key themes, concepts, and empirical findings related to passive design strategies, renewable energy integration, energy-efficient building envelopes, advanced lighting design, smart home technologies, and sustainable building materials. This thorough examination of the existing literature allowed for a comprehensive understanding of the current state-of-the-art practices and emerging trends in energy-efficient building design tailored for hot and humid climates. The findings and insights drawn from the literature study served as the basis for formulating the proposed conceptual design for energy-efficient residential units in such climatic conditions.

Climate Zone and Its Characteristics

The studied climatic zone i.e. hot and humid climate falls in Climate Zone 0B as per ASHRAE classification. It experiences warm to hot temperatures throughout the year, with minimal temperature variations between seasons. Due to the warm and humid conditions, building design considerations in Climate Zone 0B focus on strategies to manage high temperatures and humidity. Design elements include effective natural ventilation, shading devices to control solar heat gain, and materials that can withstand the tropical climate (Gamero-Salinas et al, 2021; Heidari et al, 2021). Strategies such as passive cooling and the use of energy-efficient building envelopes are important considerations for design in such areas (Heidari et al., 2021).

Energy Efficient Design Components

The components of energy-efficient building design outlined in this section encompass a range of strategies aimed at optimizing energy performance and enhancing indoor comfort in hot and humid climates. These strategies include passive design approaches, renewable energy integration, optimization of the building envelope, advanced lighting design, smart home technologies, and the use of sustainable building materials. By integrating these strategies into the design process, buildings can minimize energy consumption, reduce reliance on mechanical systems, and contribute to environmental sustainability.

Passive Design Strategies

Passive design strategies play a crucial role in building construction in hot and humid climates, helping to optimize energy efficiency and enhance indoor comfort without relying heavily on mechanical systems. Measures that can passively improve energy efficiency includes orientation of the building to avoid direct sunlight during the hottest part of the day. Thermal insulation, natural ventilation, and solar shading are also found to be effective strategies (Chen et al., 2021). Several sustainable materials such as bamboo and timber louvers and screens provide shading while allowing for natural ventilation (Mashruwala & Jadav, 2023).

Renewable Energy Integration

Renewable Energy Integration involves harnessing various sustainable energy sources such as solar, wind, ocean, hydropower, biomass, geothermal resources, and biofuels, along with hydrogen (Chel & Kaushik, 2018). Among these, Solar Energy Systems stand out for their versatility in seamlessly integrating into buildings to fulfill diverse energy needs, including heating, cooling, electricity, and lighting requirements (Akhtaruzzaman et al., 2017). Solar thermal collectors and photovoltaic panels can effectively utilize suitable surfaces like facades, horizontal roofs, and inclined roofs of buildings, maximizing solar energy capture and utilization (Hosseini et al., 2021). Additionally, advancements in solar technology, such as Building Integrated Photovoltaics (BIPV) and solar shingles, offer innovative solutions for integrating renewable energy generation into building envelopes (Hassanien et al., 2019). Integrating renewable energy sources not only reduces reliance on fossil fuels but also contributes to mitigating greenhouse gas emissions and promoting sustainable development goals (Liu et al., 2020).

Energy Efficient Building Envelope

The annual cooling requirements for buildings can be significantly reduced through effective thermal insulation, particularly in hot-dry and hot-humid climates (Aktacir et al., 2010). Employing simulation models and assessing building loads allows optimization of envelope characteristics, such as adjusting the configurations of walls, roofs, or glazing in incremental, one-parameter steps.

The building envelope, which can be made up of opaque, transparent, or a combination of both materials, plays a significant role in the energy consumption of a building for heating, cooling, and lighting purposes. Various factors, such as material conduction, solar energy transmission through windows, shading characteristics, visible transmittance, and effective aperture, influence this energy usage. Glazing systems can enable the effective use of daylight and direct solar energy gain, while opaque exterior walls can benefit from indirect gain (Hopkinson et al., 1966). Additionally, the geometric features of a building, such as its shape factor, length-to-width ratio, window-to-floor ratio, and Window-to-Wall Ratio (WWR), can also impact the building's energy load (Lee at al., 2013).

Advanced Lighting Design

Lighting contributes the highest amount of electricity usage in a building with the typical contribution ranging from 20 – 50 of total electricity use (Muhamad et al., 2013). Lighting design is more than the selection of luminaries. Advanced lighting design for energy-efficient buildings involves the strategic integration of cutting-edge technologies and design principles to optimize illumination while minimizing energy consumption. The goal is to create well-lit and comfortable spaces while reducing the environmental impact and energy costs associated with lighting. Replace traditional lighting sources with energy-efficient Light Emitting Diodes (LEDs) that consume less energy and have a longer lifespan (Ahemen et al., 2014). Ozenen (2023) suggested task-specific lighting solutions to ensure that illumination is focused where it is needed, reducing overall ambient light levels and saving energy.

Smart Home Technologies

Smart home technologies are pivotal for augmenting the energy efficiency of residential units, empowering homeowners with tools to monitor, control, and optimize energy consumption. A plethora of technologies, including Smart Thermostats, Smart lighting systems, Smart Home Energy Management Systems, Smart Power Strips, Solar Panels with Smart Inverters, Smart Windows and Blinds, Smart Appliances, Home Energy Storage Systems, and Occupancy and Motion Sensors, have emerged to revolutionize energy management within households (Belli et al., 2023; Cho et al., 2020; Kim et al., 2019; Ordoñez-Morales et al., 2018). These technologies enable real-time monitoring and adjustment of energy usage, facilitating more efficient utilization of resources and reducing energy wastage (Raza et al., 2017). Furthermore, the integration of Artificial Intelligence (AI) and machine learning algorithms enhances the adaptive capabilities of smart home systems, optimizing energy consumption patterns based on user preferences and environmental conditions (Wang et al., 2021; Yoo et al., 2022). Smart home technologies not only contribute to reducing household energy bills but also play a vital role in promoting sustainability and mitigating the environmental impact of residential energy consumption (Zhang et al., 2020).

Sustainable Building Materials

In hot and humid climates, a holistic approach that considers both construction materials and design strategies is essential. Combining the sustainable and energy-efficient building materials with proper design and landscaping can significantly contribute to creating comfortable and environmentally friendly buildings. Reflective Roof Coatings incorporates a white reflective coating on the roof. Research shows that it can significantly reduce the maximum interior surface temperature and the cooling loads (Triano-Juárez et al., 2020). Light-colored or reflective tiles can be used to minimize heat absorption. Numerous building materials derived from bamboo have been innovated to better align with contemporary construction requirements. (Manandhar et al., 2019). Hollow Clay Bricks have insulating properties and are capable of reducing heat transfer through walls (Rawat & Singh, 2022). Planted roofs provide insulation and reduce heat absorption, contributing to a cooler building interior (Bevilacqua, 2021).

Conceptual Model

Drawing upon insights from the literature review encompassing various dimensions of energy-efficient building design, a conceptual model is proposed to guide the development of energy-efficient housing units in hot and humid urban areas. The studied climatic zone, classified as Climate Zone 0B by ASHRAE, necessitates specific design considerations to manage high temperatures and humidity effectively (Gamero-Salinas et al., 2021; Heidari et al., 2021). The conceptual design integrates passive design strategies, renewable energy integration, energy-efficient building envelopes, advanced lighting design, smart home technologies, and sustainable building materials to optimize energy efficiency and enhance indoor comfort without heavy reliance on mechanical systems (Chen et al., 2021; Akhtaruzzaman et al., 2017; Hassanien et al., 2019; Raza et al., 2017; Manandhar et al., 2019).

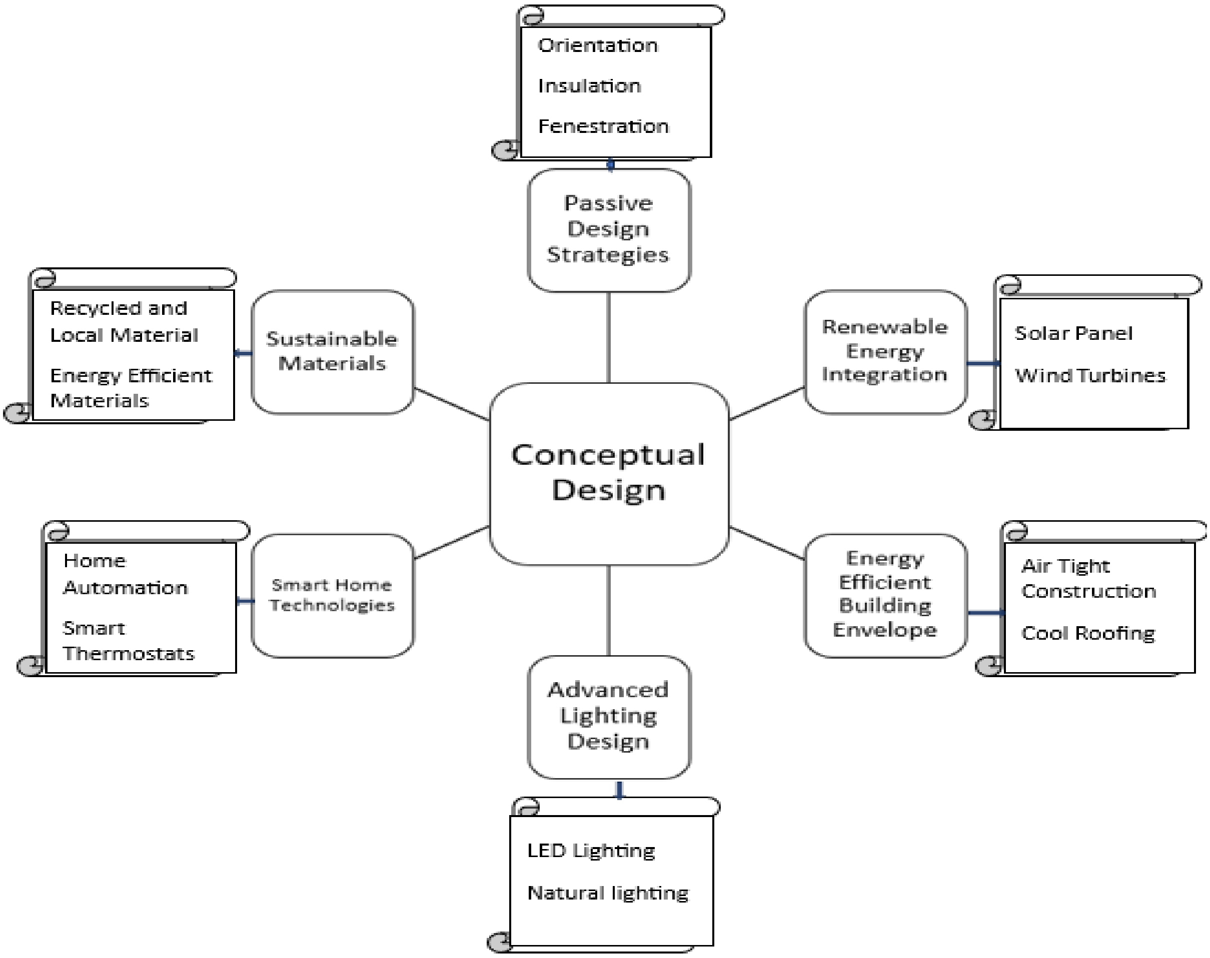

Figure 1: Conceptual design components for energy efficient buildings.

The conceptual model outlines key components essential for energy-efficient housing units, emphasizing collaborative efforts among project participants. Architects and Engineers (A/Es) are tasked with designing for efficiency, selecting sustainable materials, and integrating renewable energy solutions into the design process. Owners are encouraged to invest in energy-efficient appliances, conduct regular energy audits, and implement smart home systems for efficient controls and personalized energy management. Contractors play a crucial role in ensuring construction follows best practices for insulation, air sealing, and the proper installation of energy-efficient systems to minimize energy wastage.

This conceptual model serves as a framework for stakeholders to collaborate and implement energy-efficient design strategies tailored to the unique challenges of hot and humid urban environments, ultimately contributing to sustainable and comfortable living spaces in these regions. The development and evaluation of the model are based on a synthesis of existing literature and ongoing iterative feedback from industry experts and stakeholders to ensure its effectiveness and applicability in real-world contexts.

Conclusions

In conclusion, this paper has underscored the critical importance of implementing energy-efficient design strategies in addressing the challenges posed by hot and humid climatic conditions in urban areas. Through a comprehensive literature review, various dimensions of energy-efficient building design have been explored, encompassing passive design strategies, renewable energy integration, advanced lighting design, smart home technologies, and sustainable building materials.

The proposed conceptual model offers a holistic approach to energy-efficient housing unit design, emphasizing the integration of multiple strategies to optimize energy performance while enhancing indoor comfort and liveability. Collaboration among architects, engineers, owners, and contractors is essential for successful implementation, ensuring that energy-efficient principles are integrated at every stage of the building process.

By leveraging innovative technologies and sustainable practices, such as solar energy integration, passive cooling strategies, and smart home systems, it is possible to create buildings that not only reduce energy consumption but also contribute to environmental sustainability and climate resilience.

Moving forward, continued research and development in energy-efficient building design, coupled with policy support and public awareness initiatives, will be instrumental in driving widespread adoption of these practices. By prioritizing energy efficiency in urban development, we can mitigate the environmental impact of buildings, enhance urban resilience, and create healthier, more sustainable communities for future generations.

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References

Ahemen, I., De Dilip, K., & Amah, A. N. (2014). A review of solid state white light emitting diode and its potentials for replacing conventional lighting technologies in developing countries. *Applied physics research*, 6(2), 95.

Akhtaruzzaman, M., Hasan, K. M. F., & Lohani, A. K. (2017). Integration of renewable energy sources with building energy systems: A review. *Renewable and Sustainable Energy Reviews*, 70, 1009-1021.

Aktacir, M. A., Büyükalaca, O., & Yılmaz, T. (2010). A case study for influence of building thermal insulation on cooling load and air-conditioning system in the hot and humid regions. *Applied Energy*, 87(2), 599-607.

Bakar, N. N. A., Hassan, M. Y., Abdullah, H., Rahman, H. A., Abdullah, M. P., Hussin, F., & Bandi, M. (2015). Energy efficiency index as an indicator for measuring building energy performance: A review. *Renewable and Sustainable Energy Reviews*, 44, 1-11.

Belli, D., Barsocchi, P., & Palumbo, F. (2023). Connectivity Standards Alliance matter: State of the art and opportunities. *Internet of Things*, 101005.

Bevilacqua, P. (2021). The effectiveness of green roofs in reducing building energy consumptions across different climates. A summary of literature results. *Renewable and Sustainable Energy Reviews*, 151, 111523.

Chel, A., & Kaushik, G. (2018). Renewable energy technologies for sustainable development of energy efficient building. *Alexandria Engineering Journal*, 57(2), 655-669.

Chen, Y., Mae, M., Taniguchi, K., Kojima, T., Mori, H., Trihamdani, A. R., ... & Sasajima, Y. (2021). Performance of passive design strategies in hot and humid regions. Case study: Tangerang, Indonesia. *Journal of Asian Architecture and Building Engineering*, 20(4), 458-476.

Cho, S., Lee, S., & Lee, K. (2020). Smart home energy management system with machine learning algorithm. *Energies*, 13(9), 2182.

Gamero-Salinas, J., Monge-Barrio, A., Kishnani, N., López-Fidalgo, J., & Sánchez-Ostiz, A. (2021). Passive cooling design strategies as adaptation measures for lowering the indoor overheating risk in tropical climates. *Energy and Buildings*, 252, 111417.

Hassanien, R. H. E., El Desouky, A. M., & Samaha, M. A. (2019). A comprehensive review of building-integrated photovoltaic technologies and case study examples. *Energy Procedia*, 158, 4367-4374.

Heidari, A., Taghipour, M., & Yarmahmoodi, Z. (2021). The effect of fixed external shading devices on daylighting and thermal comfort in residential building. *Journal of Daylighting*, 8(2), 165-180.

Hopkinson, R. G., Petherbridge, P., & Longmore, J. (1966). Daylighting.

Hosseini, M. R., Fauzi, A., Mohammed, A. T., Hasanuzzaman, M., & Putrajaya, R. (2021). A review on development and performance enhancement of solar air collector integrated with PCM for building applications. *Journal of Cleaner Production*, 315, 128256.

International Energy Agency. (2023, July 11). Buildings. Retrieved from https://www.iea.org/energy-system/buildings

Kim, J., Baek, Y., & Kim, J. (2019). Development of a smart home energy management system based on internet of things. *Sustainability*, 11(9), 2610.

Lee, J. W., Jung, H. J., Park, J. Y., Lee, J. B., & Yoon, Y. (2013). Optimization of building window system in Asian regions by analyzing solar heat gain and daylighting elements. *Renewable Energy*, 50, 522-531.

Liu, S., Zhao, X., Zhang, J., & Xu, H. (2020). A comprehensive review on the integration of renewable energy systems into building energy systems. *Renewable and Sustainable Energy Reviews*, 127, 109877.

Manandhar, R., Kim, J. H., & Kim, J. T. (2019). Environmental, social and economic sustainability of bamboo and bamboo-based construction materials in buildings. *Journal of Asian Architecture and Building Engineering*, 18(2), 49-59.

Mashruwala, P., & Jadav, P. (2023, May). Impact of Passive Design Techniques on Building Performance in Improving Thermal Comfort in a Hot and Dry Climatic Zone. In Future is Urban: Livability, Resilience & Resource Conservation: *Proceedings of the International Conference on FUTURE IS URBAN: Livability, Resilience and Resource Conservation (ICFU 2021)*, December 16–18, 2021 (p. 320). Taylor & Francis.

Muhamad, W. N. W., Zain, M. Y. M., Wahab, N., Aziz, N. H. A., & Abd Kadir, R. (2010, January). Energy efficient lighting system design for building. In *2010 International Conference on Intelligent Systems, Modelling and Simulation* (pp. 282-286). IEEE.

Ordoñez-Morales, A., Campos-Cantón, E., & Reyes, A. (2018). Smart power strip for a smart home energy management system. *Energies*, 11(5), 1181.

Ozenen, G. (2023). Architectural Interior Lighting. Springer Nature.

Rawat, M., & Singh, R. N. (2022). Impact of light-colored paint materials on discomfort in a building for hot-dry climate. *Materials Today: Proceedings*, 52, 998-1005.

Raza, U., Alcaraz Calero, J. M., & Chen, Q. (2017). A review of smart homes—Past, present, and future. *IEEE Access*, 5, 26521-26544.

Triano-Juárez, J., Macias-Melo, E. V., Hernández-Pérez, I., Aguilar-Castro, K. M., & Xamán, J. (2020). Thermal behavior of a phase change material in a building roof with and without reflective coating in a warm humid zone. *Journal of Building Engineering*, 32, 101648.

Wang, X., Zhang, Y., & Liu, Z. (2021). Artificial intelligence for smart home energy management system: A review. *IEEE Access*, 9, 93756-93769.

Yoo, S., Lee, S., & Kim, S. (2022). Development of a machine learning-based smart home energy management system for demand response programs. *Energies*, 15(2), 330.

Zhang, Y., Wang, H., & Jin, X. (2020). A comprehensive review on smart home energy management system based on energy internet. *Energy Reports*, 6, 1720-1731.

Leadership in Energy and Environmental Design (LEED) vs. National Green Certification System (YES – TR) in Building Materials Category Comparison

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Abstract

The remarkable growth in advanced construction techniques has significantly increased the demand for sustainable buildings. Many countries have taken important steps in this field by introducing sustainability, green building assessment tools. Leadership in Energy and Environmental Design (LEED) is a programme initiated by the US Green Building Council. National Green Certification System (YeS-TR) is the certification system issued by the Ministry of Environment, Urbanisation and Climate Change in Turkiye. Building materials evolve with the advancement of technology and develop with the aim of having low emission, sustainable, recyclable, and aesthetic properties. The continuous development of materials has created an important context between design and cost concerns. In this study, the material category of LEED and YeS-TR green building assessment certification systems are compared with the help of tables and their common features and differences are given for the new buildings. In LEED and YeS-TR, the material category is ranked fourth in terms of points and ranking in both certification systems. Although both systems have common criteria such as sustainable material supply, waste management and use of low emission materials that encourage material selection, there are differences in scoring types. YeS-TR, which was developed by considering the conditions specific to Turkiye, includes more detailed Building Material and Life Cycle (BLC) Assessment Criteria than LEED. While both systems give high importance to the material category, it is foreseen that this category will further develop and specialise in the future.

Keywords: *green building, green building certification systems, LEED, YeS- TR, building materials.*

Introduction

The concept of green building refers to an approach that aims to consume zero energy and focuses on minimising negative impacts on the environment. The green building movement has emerged with increasing interest in environmental issues and surprising statistics. This approach has led to sustainable construction being recognised as a major area of interest and included in official projects since the early 1990s. Green building, together with concerns about the number of available resources, triggered this movement. In this context, a green building is a building constructed or remodelled using environmentally friendly design techniques, advanced technologies and materials that minimise environmental impacts (Jerry, 2008).

Different programs have been developed around the world to assess the environmental and energy impacts of buildings and to make the green building concept sustainable. The first environmental certification system was introduced in the United Kingdom in 1990 (Jerry, 2008), "The Building Research Environmental Assessment Method (BREEAM)". In 1998, the Leadership in Energy and Environmental Design (LEED) Green Building Rating System was introduced in the United States, largely based on the BREEAM system. For the first time in Turkiye, a National B.E.S.T.-Housing Certificate was developed by TGBC - Turkish Green Building Council (in Turkish: ÇEDBİK) in February 2013. It was prepared for Turkiye by analysing BREEAM and LEED certificates (TGBC, 2019).

Following these certification systems, the ‘Safe Green Building’ Certification System was published by the Turkish Standards Institute (TSE). Finally, with the regulation on ‘Procedures and Principles of Secure Green Building Certification’ published by the ‘Ministry of Environment, Urbanisation and Climate Change’ in the Official Gazette on 12 June 2022, the Green Certificate system for Buildings and Settlements was implemented and the national ‘Yes-TR Green Certificate’ system was published (MoEUCC, 2022a and 2022b).

This study will first examine the requirements and processes of LEED and YeS-TR certification systems in detail. Then, by comparing the evaluation criteria of LEED and YeS-TR certification systems, the prominent features of the material category will be determined. In the next stage, the strengths and development areas of both certification systems will be identified. This study aims to identify the differences between LEED and YeS- TR in the material category and to gain a deeper insight into the applicability of the certification process.

Green Buildings and Certification Systems

Green buildings create an environmentally friendly building by reducing environmental impacts on the building, saving energy and water. Green building design has significant impacts not only on the environment but also on human health (Yudelson, 2008). The first critical level is that green buildings directly affect an individual's health by providing optimized indoor environments. These indoor environments increase productivity, reduce stress, and improve people's overall quality of life through clean air quality, use of natural lighting and ergonomic adjustments (Pope, 1993). The second critical level is that green building designs contribute to the reduction of health problems throughout society by reducing energy use and polluting air. As a result, green buildings adopt an approach that focuses not only on environmental sustainability but also on human health (Habre, 2014). There are different certification systems for the assessment of environmental and energy impacts of green buildings.

LEED (Leadership in Energy and Environmental Design)

LEED was developed by the United States Green Building Council (USGBC) in 1998. The LEED certification approach provides a certification process for designing sustainable plans and green construction.

LEED has been in use since 1998 and as of September 2022, more than 155,423 buildings in 165 countries have LEED certification (ElSorady, 2020). Today, this number covers a total of 197,000 buildings (USGBC, 2024). The latest version of LEED is v4.1. In LEED v4.1 certification, a building earns a Certified rating with 40-49 points, Silver with 50-59 points, Gold with 60-79 points and Platinum with 80-110 points. LEED v4.1 adopts the principle of sustainability throughout the entire life cycle of the building. It also measures these sustainable principles comprehensively. LEED v4.1 offers a broader perspective by including the interior spaces of the building in the evaluation process (ElSorady, 2020). LEED v4.1 offers four different types of certificates:

- Building Design and Construction (LEED BD+C)
- Building Operation and Maintenance (LEED O+M)
- Interior Design and Construction (LEED ID+C)
- Building for Neighborhood Development (LEED ND)

This study analyses the criteria of the LEED (BD+C) certification system, which consists of nine main topics or categories. The LEED certification approach provides a certification process for the design of sustainable plans and green construction. LEED v4.1 (BD+C) categories and their corresponding points are as follows: Integrative Solution 1 point, Location and Transportation 9 points, Sustainable Sites 9 points, Water Efficiency 11 points, Energy and Atmosphere 35 points, Materials and Resources 19 points, Indoor Environmental Quality 16 points, Innovation 6 points and Regional Priority 4 points for a total of 110 points (USGBC, 2024).

LEED v4.1 (BD+C)'s "New Building's Materials and Resources" Category

LEED v4.1 (BD+C) evaluates the buildings in the certification process in "New Buildings" and "Existing Buildings" headlines. There are building typologies evaluated in each category. Given building typologies: New Construction, Core and Shell, Schools, Retail, Data Centres, Warehouses and Distribution Centres, Hospitality, Health Services (USGBC, 2024). In this study "New Building" headline is analysed (Table 1). The assessments were made according to LEED's Building Design and Construction (LEED BD+C) New Construction guidelines.

Table 1. LEED v4.1 (BD+C)'s "New Building's Material and Resources" category points.

LEED v4.1 (BD+C)'s "Material and Resources" Category's Credit / Prerequisite	New Building Points
Recyclable Materials	Prerequisite
Construction Waste Management Planning	Prerequisite
PBT Reduction - Mercury	-
Building Life Cycle Impact Mitigation	5
EPD Optimization	2

Source of Raw Material Opt.	2
Material Content Optimization	2
PBT Reduction- Pb, Cd, Cu	-
Furniture and Medical Upholstery	-
Design for Flexibility	-
Construction Waste Management	2
Total	13

In the LEED v4.1 (BD+C)'s "New Building Materials and Resources" category, Recyclable Materials must be provided with the prerequisite of Construction Waste Management Planning. Building Life Cycle Impact Reduction 5 points, EPD Optimisation 2 points, Raw Material Source Optimisation 2 points, Material Content Optimisation 2 points, Construction Waste Management 2 points, total 13 points (Table 1). The remaining items have no points. The ratio of the materials and resources category to other categories in LEED is 17% (USGBC, 2024).

YeS - TR (National Green Certification System)

YeS-TR has been contributed and its development has been supported by the Ministry of Environment, Urbanization and Climate Change, 32 academics from 11 different scientific working groups from 7 countries, universities, and many experts (Özçevik et al., 2018). It is a local assessment system for Turkiye. Its aim is to ensure that it competes with internationally recognized assessment systems all over the world. YeS-TR was announced on November 8, 2019, because of the joint work of the 'Ministry of Environment, Urbanization and Climate Change' and Istanbul Technical University (ITU).

In the first version published by YeS-TR, a guideline that can be applied in both residential areas and buildings has been prepared. There are building typologies that are evaluated in each module. The given building typologies: There are 7 types in total: Housing, Office Buildings, Education Buildings, Hotels, Health Buildings, Shopping and Trade Centres, Other. These two evaluation categories are given as 'New Building' and 'Existing Building'.

The equivalent of the main category expression in LEED is the main module in YeS-TR. YeS-TR consists of 6 main modules (MoEUCC, 2022a).

The scores for the residential building module of YeS-TR are given as follows: Integrated Building Design, Construction and Management (BBT) 15 points, Indoor Environmental Quality (IOK) 20 points, Building Material and Life Cycle Assessment (LCA - YMD in Turkish) 16 points, Energy Use and Efficiency (EKV) 25 points, Water and Waste Management (SAY) 24 points and Innovation_Bina (INO) 10 points, totalling 110 points (MoEUCC, 2022a). The YeS-TR rating system is certified as 'Pass, Good, Very Good and National Outstanding'. YeS-TR certification grades are based on the following minimum and maximum scores: 'Pass' requires 32 to less than 40 points, 'Good' requires 40 to less than 55 points, 'Very Good' requires 55 to less than 75 points, and 'National Distinguished' requires 75 or more points.

YeS - TR Crediting System

YeS-TR promotes more sustainable urban development by lending from different perspectives. At the same time, measurable criteria as well as mandatory criteria provide a flexible framework for projects to achieve their sustainability goals. YeS-TR placement grades are determined by the 'total weighted credit' points earned. Each module is assessed out of 100 credits, with a maximum of 100 credits. The credit points earned in modules are multiplied by the module's own 'weighting coefficient' to obtain the weights in the green placement. The basic grading system is based on a 'total weighted credit amount' obtained by summing the weighted credit amounts obtained for the categories (MoEUCC, 2022a).

YeS -TR’s Housing Type, Building Module’s “New Building Material and Life Cycle Assessment (YMD)” Criteria

The 'Building Material and Life Cycle Assessment' category, which is considered in the creation processes of the Green Building Guide, aims to determine the criteria that will minimise the environmental impacts of the materials used in the construction phase of sustainable buildings. These criteria generally aim to reduce the use of depleted and non-renewable natural resources, to reduce solid, liquid, and gaseous wastes resulting from technological and industrial production processes, to minimise wastes mixing with air, soil, and water, and to prevent the negative effects of the materials selected in the formation process of the building on human health. In this way, it is aimed to minimise environmental impacts and contribute positively to human health through the selection and application of materials used in sustainable building projects (MoEUCC, 2022a). YeS-TR “Building Material and Life Cycle Assessment (LCA-Turkish LCA)” is evaluated with 7 categories that are given in Table 2 below with their points.

Table 2. YeS-TR’s housing type, building module’s “New Building Material and Life Cycle Assessment (LCA- in Turkish YMD)” criteria points.

YeS-TR’s Housing Type, Building Module’s “New Building Material and Life Cycle Assessment (YMD)” Criteria	Points
YMD 01Building Material Life Cycle Assessment (CUB) and Environmental Product Declaration	25
YMD 02 Healthy Product Declaration (SUB)	21
YMD 03 Radiation Release	5
YMD 04 Responsible Sourcing	8
YMD 05 Local Sourcing	6
YMD 06 Use of Reused, Reclaimed or Recyclable Materials	26
YMD 07 Use of Durable Materials	9
Total	100

Comparison of LEED and YeS-TR’s Material Categories

The LEED and YeS-TR systems are green building certification systems with different schemes for various building typologies. The LEED certification system was established in 1998 in the United States by the U.S. Green Building Council (U.S. Green Building Council (USGBC). YeS-TR was published by the Ministry of Environment, Urbanization and Climate Change in 2021 in Turkiye (MoEUCC, 2022a).

Both systems are divided into environmental categories and sub-categories, with a specific number of points or credits for each, and the total points of both categories is 110.

LEED v4.1 offers a category with 9 main headings which are called categories. These main headings have different subheadings within themselves. Each different main heading has its own credit score (Ahankoob, 2013). The sum of the credit score given is 110. YeS-TR has 6 different main modules in the building module. Since LEED v4.1 is an international green building certification system, the points given to each country are equal, but the conditions of each country are not equal (Karademir, 2021). Since YeS-TR is a national green certification system, the points are given in accordance with the conditions of the country. LEED, on the other hand, was scored according to the American region.

According to Gultekin and Bulut (2015), while the protection of water resources is a higher priority in some countries, land use is more important for others. Since such priorities vary according to each country, the application of weighting coefficient is important. In this way, national and regional priorities can be prioritised according to each country and contribute to the elimination of the problems there. Since YeS-TR has this weight coefficient, each country can point according to its own priority.

The assessment of construction materials determined by YMD 01 K1 targets environmentally, economically, and socially beneficial products. Total points are 25. YMD 02 Health Product Declaration (SUB) under K1, K2 prioritises indoor air quality with 21 points. Radiation Emission (YMD 03) aims at user safety with 5 points. Responsible Sourcing (RES 04) provides efficient, sustainable use of materials with 8 points. Local Sourcing (YMD 05) minimises environmental impact and is assessed with 6 points. YMD 06 promotes the use of Recycled Materials with 26 points and YMD 07 focuses on Durable Materials with 7 points. Total module value 100 (Table 3).

Table 3. Comparison of LEED v4.1 (BD+C)'s "New Building's Material and Resources" category and YeS-TR's housing type, building module's "New Building Material and Life Cycle Assessment (LCA- in Turkish YMD)" criteria category.

LEED v4.1 (BD+C)'s "New Building's Material and Resources" Credit / Prerequisite	New Building - Points	YeS-TR "Building Material and Life Cycle Assessment (LCA- in Turkish YMD)" Credit / Prerequisite	New Building - Points
Recyclable Materials	Prerequisite	YMD 06 Use of Reused, Recycled or Recyclable Materials	26
Construction Waste Management Planning	Prerequisite	-	-
PBT Reduction - Mercury	-	-	-
Building Life Cycle Impact Mitigation	5	YMD 01Building Material Life Cycle Assessment (YDD) and Environmental Product Declaration	25
EPD Optimisation	2	-	-
Source of Raw Material Optimization	2	YMD 04 Responsible Sourcing	8
Material Content Optimisation	2	YMD 02 Healthy Product Declaration (SUB)	21
PBT Reduction- Pb, Cd, Cu	-	-	-
Furniture and Medical Upholstery		-	-
Design for Flexibility	-	-	-
Construction Waste Management	2	-	-
-	-	YMD 03 Radiation Release	5
-	-	YMD 05 Local Sourcing	6
-	-	YMD 07 Use of Durable Materials	9
Total	13	Total	100

LEED Material Category points total 13, while YeS-TR offers 16. YeS-TR references TS, ISO, and EN standards, favoring local materials and avoiding international procurement, thus reducing carbon footprint. LEED requires materials within 500 miles, challenging in Turkey, while YeS-TR's local sourcing criterion is 200 km. While LEED emphasises recyclable materials as a prerequisite, YeS-TR requires the use of 5% recycled materials from different sources (MoEUCC, 2022b). YeS-TR's construction and waste management planning requires documentation of 20% of material costs, exceeding LEED's recycled materials criterion (USGBC, 2019; MoEUCC, 2022b). YeS-TR's "Healthy Product Declaration" module offers a more detailed approach with 21 points, replacing LEED's PBT Mitigation categories (MoEUCC, 2022b). In terms of building life cycle impact mitigation, the criteria of YeS-TR are more comprehensive, giving 25 points compared to the 5 points given in LEED (MoEUCC, 2022b). While LEED's criteria are based on American conditions, YeS-TR considers local factors and potentially produces better results (Erten, 2009; Erdede et al., 2014; Kurnaz, 2021).

Results

The use of building materials evolves with technology, aiming for low emissions, sustainability, recyclability, and aesthetics. Both LEED and YeS-TR prioritise material criteria, reflecting the importance of material selection in design and cost concerns. Although they share common criteria such as material reuse and sustainable sourcing, YeS-TR's Building Material and Life Cycle Assessment Criteria provide more detail than LEED's Materials and Resources category. Despite their differences, both certification systems have common features and aim to meet country-specific needs. While LEED has been applied internationally since 1998, YeS-TR, which was introduced in 2022, aims to develop internationally by adapting to Turkey's construction sector and local conditions.

Conclusion

While LEED and YeS-TR certification systems both prioritise the material category, LEED v4.1 is becoming more detailed over time. YeS-TR offers a more comprehensive approach compared to LEED's 13-point system with a total of 100 points and 7 sub-criteria. However, YeS-TR lacks the modules for location and transport and sustainable sites found in LEED, indicating some shortcomings in urban context scoring and environmental impact mitigation. Nevertheless, YeS-TR surpasses LEED in this respect by encouraging recycling in water and waste management.

The widespread use of LEED globally enables regional adaptation, reconsiders limits such as 500 mile radius for material sourcing, and contributes to its ongoing development. In contrast, YeS-TR's focus on local materials within 200 km encourages regional sustainability.

As the number of LEED certified projects in Turkey increases, supporting YeS-TR is vital to promote environmentally friendly building practices. Improvements to YeS-TR, particularly in areas such as location and transport, are expected to increase compliance with international standards and promote sustainability in construction projects.

References

Ahankoob, A., Morshedi.E, S. R., & Golchin Rad, K. (2013). A Comprehensive Comparison between LEED and BCA Green Mark as Green Building Assessment Tools. The International *Journal of Engineering and Science*, 31-38.

Elsorady, D., & Rizk, S. (2020). LEED v4.1 operations & maintenance for existing buildings and compliance assessment: Bayt Al-Suhaymi, Historic Cairo. *Alexandria Engineering Journal*, 59, 10.1016/j.aej.2020.01.027.

Erdede, SB, Erdede, B., & Bektaş, S. (2014). Sustainable green buildings and evaluation of certification results. Remote Sensing-Cbs Symposium (UZAL-CBS 2014), 14 (17), 17-32. Retrieved from https://www.set-science.com/manage/uploads/ISAS2018-Winter_0039/SETSCI_ISAS2018-Winter_0039_0025.pdf

Erten, D. (2009). Green building certification and solution proposals for Turkey. Yapı Magazine Yapıda Ecology Supplement, 329, 50-55. https://avesis.medipol.edu.tr/yayin/557589e2-fd7e-4de7-96bd-509cd2667ad0/turkiye-icin-yesil-bina-sertifikasi-ve-cozum-onerileri

Gültekin, A.B., & Bulut, B. (2015). Green Building Certification Systems: A System Proposal for Turkey. *2nd International Symposium on Sustainable Buildings (ISBS)*, Ankara. Retrieved from https://avesis.gazi.edu.tr/yayin/0cf5b3ec-4991-4088-a6e5-b8f6b88d5606/yesil-bina-sertifika-sistemleri-turkiye-icin-bir-sistem-onerisi

Jerry, Y. (2008). What is a Green Building. In The Green Building Revolution (Chapter 2). https://dev.ecoguineafoundation.com/uploads/5/4/1/5/5415260/the_green_building_revolution.pdf. Island Press.

Karademir, A. Ç., & Dağ, A. (2021). A Study on Green Building and LEED Certification as a Sustainability Practice in the Construction Sector in Turkey. *Akademia Journal of Nature and Human Sciences*, 7(1), 63-83. https://dergipark.org.tr/tr/pub/adibd/issue/60270/948527

Kurnaz, A. (2021). Green Building Certificate Systems as A Greenwashing Strategy In Architecture. *Bartın University International Journal of Natural and Applied Sciences*, 4(1), 72-88. Retrieved from: https://dergipark.org.tr/tr/pub/jonas/issue/60051/892270#article_cite

MoEUCC (2022a). T.C. Ministry of Environment, Urbanisation and Climate Change, Green Certificate Evaluation Guide, 12 June, Annex 1 of Official Gazette No. 31864, Ankara, Turkiye.

MoEUCC (2022b). Republic of Turkey Ministry of Environment, Urbanisation and Climate Change. Regulation on Green Certificate for Buildings and Settlements. Official Gazette dated 12.06.2022 and numbered 31864. https://www.resmigazete.gov.tr/eskiler/2022/06/20220612-1

Pope, C., Xu, X., et al. (1993). An association between air pollution and mortality in six U.S. cities. *New England Journal of Medicine*, 329(24), 1753–1759.

Sharp, P. (1992). Energy policy act of 1992. Accessed 21 February 2019. Retrieved from https://afdc.energy.gov/files/pdfs/2527.pdf

TSI - Turkish Standards Institution (2014). TSI Product Certification Services, Turkish Standards Institute Principles and Methods for Safe-Green Building Certification. Retrieved from https://www.tse.org.tr/urun-belgelendirme-hizmetleri/

USGBC - United States Green Building Council. (2024). USGBC Web Site. Retrieved from https://www.usgbc.org/leed

USGBC - United States Green Building Council. (2019). LEED v4.1 for Operations & Maintenance: Existing Buildings. Retrieved from https://www.usgbc.org/leed/v41

Yudelson, J. (2008). The Green Building Revolution. Washington: Island Press, ABD. Washington: Island Press, ABD.

Off-site Construction Industry Through the Lens of Circular Economy

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Abstract

Off-site construction (OSC) methods have been receiving a lot of attention nowadays because of their many benefits, which include lower construction costs and times, increased efficiency, and protection of the environment. In OSC processes, which generally proceed with modern construction methods, materials can be recycled more easily at the end of their life. This contributes to the Circular Economy (CE) approach, which aims at economic growth without increasing resource use in the construction industry. However, CE is not just about material transformation. A multi-focused approach is required to implement this approach, which covers the entire design, construction, operating, and demolition processes. In this study, applied CE approaches were determined through literature analysis. Circularity applications that can be used for OSC are expressed under functions, products, components, materials, energy, and referential circularity. The paper's theoretical value relies on providing a foundation for upcoming studies on the CE of the construction industry. The study's practical contribution is to guide OSC stakeholders on how to increase OSC circularity.

Keywords: *circular economy, circularity, off-site construction.*

Introduction

The world is facing the challenge of climate change, which is being caused by global warming. To combat this, there have been significant sustainable innovations that focus on reducing carbon emissions from production and waste disposal. In 2015, the Paris Agreement was signed, and in 2016, the United Nations released the Sustainable Development Goals (SDGs) to set targets for global development by 2030 and 2050. The rate of resource consumption on Earth is unsustainable and will require three times the available resources by 2050 (Peter Lacy, 2015). To halt this adverse trend, production industries must act and adhere to current sustainability approaches and goals.

Construction and demolition waste account for 36% of total waste, while buildings consume 40% of the total energy expended (Wilson et al., 2019). This underscores the urgency for the construction industry to transition to sustainable practices. Enhancing the lifecycle of construction industry products through circular economy principles can reduce waste consumption. Efforts towards Circular Economy (CE) in the construction industry are underway (Çetin et al., 2021). However, despite these efforts, the global circularity rate decreased from 9.1% in 2018 to 8.6% in 2020 (The Circularity Gap Report, 2022). This indicates that current endeavors may be insufficient, and there is a lack of clarity on how circular economy principles can be effectively applied in the construction industry (Nußholz et al., 2023).

This study focuses on Circular Off-Site Construction (COSC), recognizing off-site construction (OSC) as a promising avenue for enhancing circularity in the construction industry. Initially, implementations related to CE were examined. Subsequently, a literature review analysis was conducted to determine the perspectives and categorizations required for implementing circular economy principles in the off-site construction industry. The research addresses significant gaps in the existing literature and aims to make pertinent contributions to the advancement of circular economy practices in the construction industry.

Philosophy of Circular Economy in Off-site Construction Industry

Implementing CE within the built environment offers benefits such as reducing the consumption of natural resources, minimizing waste generation, and cutting down greenhouse gas emissions. Incorporating CE principles, operations, and business models into the entire lifecycle of construction projects—from planning and design to construction, operation, maintenance, and deconstruction—opens new avenues to separate construction activities from the consumption and exhaustion of finite resources. Circular construction embraces CE principles, strategies, and goals to disconnect construction activities and practices from finite resource depletion, economic inefficiencies, and negative social impacts (Ellen MacArthur Foundation, 2015).

Circular construction is grounded in the principles of industrial ecology, industrial symbiosis, reverse logistics, the cradle-to-cradle concept of effectiveness, cleaner production, and closed-loop material flows (Sehnem et al., 2019). It employs interconnected strategies of narrowing, slowing, and closing resource loops to reduce the wasteful use of natural resources, prevent waste and pollution from the beginning, and extend the lifespan of construction materials and products (Hopkinson et al., 2019). Despite these potential benefits, the adoption of circular economy principles in construction projects has been challenging for construction professionals.

In recent years, various life cycle assessment approaches have been developed, including methods such as cradle to cradle, cradle to gate, and gate to gate. Life cycle approaches typically focus on resource extraction and material flow, considering various starting and ending points within a product's life cycle (Moraga et al., 2019). However, resource-centric and production-centric approaches do not encompass pre-production stages such as feasibility, planning, and design in the building life cycle (Bak et al., 2016). In this context, construction organizations differ from organizations in other industries, as the construction industry is unique because of its project-based nature. Considering the new approach of CE, there is a need for a fresh perspective on life cycle approaches to shift our focus from product manufacturing to solution creation (Çimen, 2023).

Transitioning to CE is increasingly recognized as an imperative for sustainable development, necessitating the adoption of a multifaceted framework. This framework is anchored on three pivotal strategies: closing, slowing, and narrowing/reducing loop (Bocken et al., 2016). Furthermore, the successful realization of a CE transition is contingent upon three core pillars: technical innovation, business model innovation, and collaboration. The strategy of closing loop involves the establishment of a circular flow of resources that come out of the post-consumption phase, traditionally categorized as waste (Hopkinson et al., 2019). This necessitates the implementation of robust recycling processes to reintroduce these resources back into the production cycle, thereby minimizing waste and maximizing resource efficiency. Conversely, the slowing loop strategy emphasizes the extension of product lifespans through deliberate interventions such as repair, refurbishment, and remanufacturing (Stahel, 2010). By promoting these actions, the strategy aims to enhance product reuse and durability, thereby reducing the demand for new resources and diminishing environmental impact. Lastly, the narrowing loop strategy is geared towards resource minimization and efficiency optimization within production processes. This involves streamlining operations to reduce resource consumption while maximizing output, thus achieving a more sustainable and efficient production paradigm (Bocken et al., 2016).

Owusu-Manu (2021) delineated eight key parameters indicative of urban sustainability: air quality, energy consumption, sanitation, land use efficiency, water management, health and safety measures, transportation systems, and building and construction practices. Meanwhile, Mhatre et al. (2021) pinpointed pivotal emerging trends in the construction industry, including energy efficiency, waste management, key enablers and drivers, end-of-life management strategies, utilization of alternative construction materials, and adoption of circular business models. Thus, the construction industry plays an important role in the advancement of smart cities. Nevertheless, despite these advancements, Çimen (2023) contends that the construction industry faces challenges in fully embracing circular economy principles.

Transitioning from a linear to a circular economy presents significant challenges due to the inherent risks associated with novel approaches. To mitigate these risks, there is an urgent need for the adoption of new technologies and innovative supply chain processes. Kazancoglu et al. (2023) explore the potential risks of this transition and identify strategies to mitigate them through the application of Industry 4.0 technologies. Their research focuses on Turkish logistics companies, and their findings underscore the importance of integrated business processes, modular simplification, and continuous monitoring of costs and performance throughout the supply chain. The construction industry requires a comprehensive evaluation framework for sustainable development. It is imperative to incorporate intentional design strategies that encompass thorough assessments of the potential environmental and societal impacts from the outset of product development. In the context of partition systems in modular construction, (Antwi-Afari et al., 2023) aim to identify a circular model through a rigorous iterative process.

The applicability of modular construction for various types of buildings highlights its environmental performance as a significant dimension of sustainability. Kamali and Hewage (2016) have concluded that modular buildings exhibit better life cycle performance in factors such as energy efficiency. To obtain a comprehensive understanding of the sustainability of modular construction, further life cycle research encompassing all sustainable construction dimensions is recommended. Off-site construction (OSC) is recognized as an effective method to enhance construction quality and efficiency. Mao (2015) identified the absence of government regulations and incentives, high initial costs, and dependency on traditional construction methods as the top three barriers to the increase of OSC. However, off-site construction methods have gained popularity in the past decade, and until 2018, no major market exceeded 20% utilization of OSC (Jayawardana et al., 2023). Nevertheless, the increasing adoption of OSC is driven by its ability to reduce construction time and costs while enhancing environmental performance. Therefore, project management from the planning and design stages onwards, along with contractors taking leadership roles, are necessary for this transition (Wuni & Shen, 2022).

The literature review demonstrates that although CE is implemented to a limited extent in the construction industry, there is a clear need for its adoption. Due to the complex and multidisciplinary nature of the construction industry, project efficiency rates are often low. Each project's unique nature has historically confined it to traditional methods for years. However, the increasing demand for off-site construction due to modern construction methods has frequently brought about more sustainable construction solutions. From this perspective, it has been observed that off-site construction is preferred to efficiently implement CE in the construction industry, and improvements made in these areas can yield more circular outcomes. From this perspective, it has been observed that off-site construction is preferred to efficiently implement CE in the construction industry, and improvements made in these areas can yield more circular outcomes. This situation highlights the interplay among sustainability, off-site construction, and circular construction concepts (Figure 1). While the visual on the left represents the volume of these concepts within the construction industry, the one on the right illustrates the increase in off-site construction in a construction industry that has achieved Sustainable Development Goals.

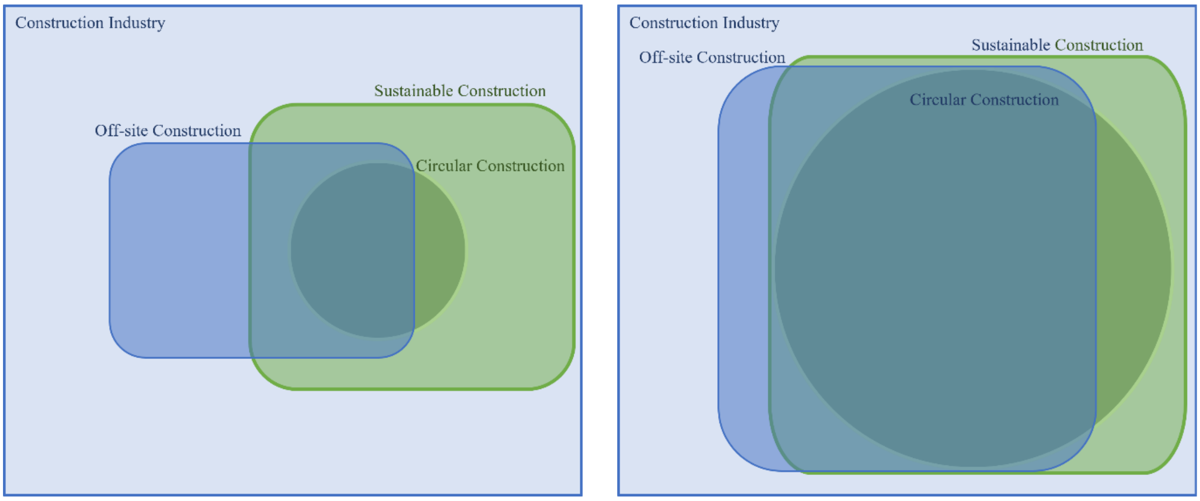

Figure 1: Position of the circular economy within the realm of sustainability and off-site construction.

Literature Review Analysis

In this study, a systematic literature review approach was employed to identify relevant studies for the implementation of CE that could benefit from OSC. The Scopus database was selected for this comprehensive literature evaluation due to its widespread usage, thorough coverage, and efficiency (Makabate et al., 2022).To address the research gap regarding the implementation of CE at OSC projects, the following search code was initially considered for CE: (TITLE-ABS-KEY ("circular economy") AND TITLE-ABS-KEY (construction) AND TITLE-ABS-KEY (off-site) OR TITLE-ABS-KEY (offsite) OR TITLE-ABS-KEY (modular) OR TITLE-ABS-KEY (prefabricate)) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English")). This search totally retrieved 45 documents that have been published until January 2024. By using the snowballing method with a systematic literature review, promising benefits emerge (Soares et al., 2023). Finally, 59 documents underwent a comprehensive examination. Utilizing this review, a study including CE practices and brief explanations of these approaches is presented in Table 1.

Table 1. Circular economy implementations in existing literature.

Philosophical Approaches of CE	**Explanation of the philosophy**	**Reference**
Material flow model	The materials flow model consists of three interconnected cycling loops, encompassing natural materials, bio-compatible materials, and non-bio-compatible materials.	Kenneth Geiser, 2001
3R framework	Established an economic mechanism to replace the concept of "end-of-life" with the reduction, reuse, and recycling of materials in manufacturing, distribution, and consumption processes.	Allwood et al., 2011
4R framework	Official EU policy framework for CE. Which ads “recovery” to most commonly 3R (reduction, reuse, recycling).	Kirchherr et al., 2017
6Rs framework	The R concept is expanded to the 6-R (with the addition of redesign and remanufacture)	Sihvonen & Ritola, 2015
9Rs framework	Later evolved into the 9-R concept (with the further addition of refurbish, repair and refuse).	Khaw-Ngern et al., 2021
10Rs framework	Principles of sustainable resource management and waste reduction.	Potting et al., 2017
Slowing Resource Loops	Extends the lifespan of products and slow down the flow of resources by promoting long-lasting goods and product life extension services like repair and remanufacturing.	Stahel, 2010
Closing Resource Loops	Value creation is to recover and reuse building products from end-of-service-life buildings.	Hopkinson et al., 2019
Narrowing Resource Loops	Reducing the product's and the production process's consumption of resources. Reusing materials requires using techniques like recycling. In contrast to slowing loops, it doesn't affect product flow speed or entail service loops like repairs.	Bocken et al., 2016
Macro-system	This perspective emphasizes the necessity to adapt the industrial composition and structure of the entire economy.	Kirchherr et al., 2017
Meso-systems	The typical perspective centers on eco-industrial parks as systems.	Shi et al., 2010
Micro-systems	Examines goods, individual businesses, and the necessary steps for enhancement.	Jackson et al., 2014
ReSOLVE	The framework applies the fundamental circular principles to six actions (Regenerate, Share, Optimize, Loop, Virtualize, and Exchange), which enhance the use of physical assets, extend their lifespan, and transition resource utilization from finite to renewable sources.	Ellen MacArthur Foundation, 2015
6 CE Principles	It defines a fundamental collection of six CE principles (system thinking, stewardship, transparency, collaboration, innovation, value optimization) to which all organizations are recommended to adhere.	British Standards Institution, 2017
CE implementation in businesses, organizations, and production systems.	A dashboard was developed to facilitate the implementation of sustainable consumer products in businesses, organizations, and production systems, utilizing various indicators, including those related to restoration, regeneration, utility maintenance, financial value preservation, non-financial value preservation, resource efficiency, climate, energy, and sufficiency	Pauliuk, 2018
CE monitoring framework	Proposed framework categorizes and classifies indicators based on the logic of what and how, encompassing functions, products, components, materials, embodied energy, and a reference scenario.	Moraga et al., 2019

Various approaches have been observed in implementing circular practices that would benefit the CE. While these approaches all ultimately contribute to circularity, it is essential to comprehensively address OSC from the planning and design stages to enhance its applicability and efficiency for CE (Wuni & Shen, 2022). Therefore, a holistic evaluation of CE, drawing from the study of Moraga et al. (2019), is imperative in enhancing its contribution to the Circular Economy within the construction industry. The potential contributions are further discussed in the concluding section.

Results

The research has categorized studies into six main themes for COSC, as follows: Functional Circularity, Product Circularity, Componential Circularity, Materials Circularity, Energy Circularity, and Referential Circularity. Within this framework, the discussions revolve around the nature of studies that could be conducted under each of these headings, drawing upon existing literature in the field.

The Circularity Gap Report (2022) has identified seven societal needs and wants: housing, services, nutrition, healthcare, mobility, communication, and consumables. Construction and repair of housing, particularly in low-income countries, account for the largest share of resources and emissions. Circular economy entails not only adhering to its own functions but also serving other functions, thereby increasing circularity rates. From this perspective, when evaluating circularity, industries should be able to achieve functional circularity across industries. For instance, in the textile industry, it is known that some materials used as waste can be utilized in the construction industry for insulation materials or asphalt production. This practice allows for raw material consumption to be facilitated across different industry functions.

However, the definition of Products Circularity differs slightly in this context. For example, the product of the construction industry is the structures resulting from construction projects. Compared to other industries, the product (i.e., the structure) has one of the longest lifespans in terms of usage. In other words, it is a production industry where resources are embedded within the product. From this perspective, product-level circularity can be divided into two categories: the circularity of existing projects and the suitability for circularity in future projects. For instance, the interior of an old building can be redesigned for more efficient use, and energy efficiency measures can be implemented to renew the structure. Furthermore, careful consideration should be given during the planning and design stages of future construction projects to ensure circularity. For example, the ability for shared spaces to accommodate various needs and adapt to different purposes could enhance the project's circularity (López Ruiz et al., 2020). Additionally, in the biological aspect of circularity, the facility management processes of these buildings represent another area that can contribute to product circularity.

In the realm of building components, the focus often gravitates towards structural systems, particularly in traditional construction, where reinforced concrete columns and steel reinforcements prevail. However, contemporary construction methodologies and the expanding array of materials have led to the emergence of diverse components tailored to the specific functional requirements of the structure. Among these are exterior elements, thermal insulation modules, and ventilation units. Modular choices are viewed as advantageous within the scope of Componential Circularity. Nonetheless, it is paramount to emphasize the importance of the accuracy and preservation of Disassembly Manual Document data (Minunno et al., 2020), as they play a pivotal role in facilitating efficient disassembly processes. Furthermore, leveraging technologies employed for building digitalization holds promise for curbing various forms of raw material consumption associated with building components.

The inception of the circular economy can arguably be traced back to the initial selection of materials. However, in the process of product creation, material choices are often driven more by profit motives than sustainability criteria. Consequently, a system emerges wherein consumer demand influences producers' material preferences. From this perspective, the concept of Material Circularity, which revolves around materials within the construction industry, holds significant importance. It is crucial to recognize that the circular economy's widely utilized method, recycling, may not always be inherently environmentally friendly. If the quality of waste materials is low, the recycling process could have more adverse environmental impacts compared to energy recovery (Huysman et al., 2015).

The energy footprint of materials and products encompasses not only the energy expended in their production, logistics, or manufacturing processes but also the energy consumed throughout facility management and even during decommissioning, or transformation processes. Ensuring energy is consumed from the correct source and in the appropriate quantity is essential for conserving resources and utilizing them efficiently. From this perspective, conducting an embedded energy analysis of materials contributes to establishing comparability from a circular economy standpoint and falls under the Energy Circularity category. Furthermore, within the framework of the butterfly diagram, the conversion of organic waste into bioenergy, as part of the biological cycle, identified as the second wing of the circular economy, can also be addressed under this heading (Ellen MacArthur Foundation, 2015).

Transitioning from a linear economy model, characterized by the "take-make-use-dispose" approach, to the "Reduce-Reuse-Recycle" production model, as advocated by the circular economy, aims to foster sustainability. In this regard, the linear economy provides a reference point for comparability in terms of circularity, considering the products it generates. When conducting this circularity comparison, criteria for contractor selection should be established based on their contribution to circularity. For instance, if a product contributes to the circular economy but incurs prohibitively high costs or has the potential to undermine circularity through indirect impacts due to its usage, it may cease to be considered an effective circular economy product. Therefore, under the title of Referential Circularity, certain technical or qualitative information pertaining to production should be included to facilitate this assessment.

Although this study has conducted a comprehensive literature review on CE practices, further strengthening the academic foundation of the study can be achieved by discussing and refining the proposed categorization with CE experts. Consequently, in-depth discussions with experts would enhance the academic rigor of the research. This would pave the way for further advancing the study topic to make CE more effective in One-Stop Centers (OSCs) productions in future research endeavors. Under these headings, developing criteria for a balanced scorecard on the circular economy or preparing a strategy map for the industry could be feasible. Additionally, depending on the scope of the studies, the findings could be utilized to provide infrastructure for various decision-making processes for OSC stakeholders.

References

Allwood, J. M., Ashby, M. F., Gutowski, T. G., & Worrell, E. (2011). Material efficiency: A white paper. *Resources, Conservation and Recycling*, *55*(3), 362–381.

Antwi-Afari, P., Ng, S. T., & Chen, J. (2023). Determining the optimal partition system of a modular building from a circular economy perspective: A multicriteria decision-making process. *Renewable and Sustainable Energy Reviews*, *185*, 113601.

Bak, S. H., Rask, N., & Risi, S. (2016). *Towards adaptive evolutionary architecture* (pp. 47–62).

Bocken, N. M. P., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, *33*(5), 308–320.

British Standards Institution. (2017). *Framework for implementing the principles of the circular economy in organizations - guide*. BSI Standards Limited .

Çetin, S., De Wolf, C., & Bocken, N. (2021). Circular digital built environment: An emerging framework. *Sustainability (Switzerland)*, *13*(11).

Çimen, Ö. (2023). Development of a circular building lifecycle framework: Inception to circulation. *Results in Engineering*, *17*, 100861.

Ellen MacArthur Foundation. (2015). *Towards a circular economy: Business rationale for an accelerated transition.* https://ellenmacarthurfoundation.org/publications/towards-a-circular-economy-business-rationale-for-an-accelerated-transition.

Geiser, K. (2001). Materials matter: Toward a sustainable materials policy. *MIT press.*

Hopkinson, P., Chen, H.-M., Zhou, K., Wang, Y., & Lam, D. (2019). Recovery and reuse of structural products from end-of-life buildings. *Proceedings of the Institution of Civil Engineers - Engineering Sustainability*, *172*(3), 119–128.

Huysman, S., Debaveye, S., Schaubroeck, T., Meester, S. De, Ardente, F., Mathieux, F., & Dewulf, J. (2015). The recyclability benefit rate of closed-loop and open-loop systems: A case study on plastic recycling in Flanders. *Resources, Conservation and Recycling*, *101*, 53–60.

Jackson, M., Lederwasch, A., & Giurco, D. (2014). Transitions in theory and practice: Managing metals in the circular economy. *Resources*, *3*(3), 516–543.

Jayawardana, J., Kulatunga, A. K., Jayasinghe, J. A. S. C., Sandanayake, M., & Zhang, G. (2023). Environmental sustainability of off-site construction in developed and developing regions: A systematic review. *Journal of Architectural Engineering*, *29*(2).

Kamali, M., & Hewage, K. (2016). Life cycle performance of modular buildings: A critical review. *Renewable and Sustainable Energy Reviews*, *62*, 1171–1183.

Kazancoglu, Y., Ozkan-Ozen, Y. D., Sagnak, M., Kazancoglu, I., & Dora, M. (2023).

Framework for a sustainable supply chain to overcome risks in transition to a circular economy through Industry 4.0. *Production Planning & Control*, *34*(10), 902–917.

Khaw-Ngern, K., Peuchthonglang, P., Klomkul, L., & Khaw-Ngern, C. (2021). The 9Rs strategies for the circular economy 3.0. *Psychology and Education*, *58*(1), 1440–1446.

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, *127*, 221–232.

López Ruiz, L. A., Roca Ramón, X., & Gassó Domingo, S. (2020). The circular economy in the construction and demolition waste sector – A review and an integrative model approach. *Journal of Cleaner Production*, *248*.

Makabate, C. T., Musonda, I., Okoro, C. S., & Chileshe, N. (2022). Scientometric analysis of BIM adoption by SMEs in the architecture, construction and engineering sector. *Engineering, Construction and Architectural Management*, *29*(1), 179–203.

Mao, C., Shen, Q., Pan, W., & Ye, K. (2015). Major barriers to off-site construction: The developer's perspective in China. *Journal of Management in Engineering*, *31*(3).

Mhatre, P., Gedam, V., Unnikrishnan, S., & Verma, S. (2021). Circular economy in built environment – Literature review and theory development. *Journal of Building Engineering*, *35*, 101995.

Minunno, R., O'Grady, T., Morrison, G. M., & Gruner, R. L. (2020). Exploring environmental benefits of reuse and recycle practices: A circular economy case study of a modular building. *Resources, Conservation and Recycling*, *160*, 104855.

Moraga, G., Huysveld, S., Mathieux, F., Blengini, G. A., Alaerts, L., Van Acker, K., de Meester, S., & Dewulf, J. (2019). Circular economy indicators: What do they measure? *Resources, Conservation and Recycling*, *146*, 452–461.

Nußholz, J., Çetin, S., Eberhardt, L., De Wolf, C., & Bocken, N. (2023). From circular strategies to actions: 65 European circular building cases and their decarbonisation potential. *Resources, Conservation and Recycling Advances*, *17*.

Owusu-Manu, D.-G., Debrah, C., Oduro-Ofori, E., Edwards, D. J., & Antwi-Afari, P. (2021). Attributable indicators for measuring the level of greenness of cities in developing countries: Lessons from Ghana. *Journal of Engineering, Design and Technology*, *19*(3), 625–646.

Pauliuk, S. (2018). Critical appraisal of the circular economy standard BS 8001:2017 and a dashboard of quantitative system indicators for its implementation in organizations. *Resources, Conservation and Recycling*, *129*, 81–92.

Peter Lacy, J. R. B. L. (2015). *Circular economy: Dallo spreco al valore*.

Potting, J., Hekkert, M., Worrell, E., & Hanemaaijer, A. (2017). *Circular economy: Measuring innovation in the product chain policy report*.

Sehnem, S., Vazquez-Brust, D., Pereira, S. C. F., & Campos, L. M. S. (2019). Circular economy: Benefits, impacts and overlapping. *Supply Chain Management: An International Journal*, *24*(6), 784–804.

Shi, H., Chertow, M., & Song, Y. (2010). Developing country experience with eco-industrial parks: A case study of the Tianjin economic-technological development area in China. *Journal of Cleaner Production*, *18*(3), 191–199.

Sihvonen, S., & Ritola, T. (2015). Conceptualizing ReX for aggregating end-of-life strategies in product development. *Procedia CIRP*, *29*, 639–644.

Soares, A. L., Buttigieg, S. C., Bak, B., McFadden, S., Hughes, C., McClure, P., Couto, J. G., & Bravo, I. (2023). A review of the applicability of current green practices in healthcare facilities. *International Journal of Health Policy and Management*, *12,* 6947.

Stahel, W. R. (2010). *The performance economy: 2nd edition*. https://doi.org/https://doi.org/10.1057/9780230274907

The Circularity Gap Report. (2022). https://www.circularity-gap.world/2022

Wilson, D. C. (David C., United Nations Environment Programme, & International Solid Waste Association. (2019). *Global waste management outlook.*

Wuni, I. Y., & Shen, G. Q. (2022). Developing critical success factors for integrating circular economy into modular construction projects in Hong Kong. *Sustainable Production and Consumption*, *29*, 574–587.

Climate Resilience in Smart City Strategies: The case of Türkiye

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Abstract

Climate resilience is of paramount importance for cities to be prepared for chronic and acute impacts of climate change, including extreme events and disasters. Smart city applications can be designed and implemented to account for climate resilience. Therefore, authorities around the globe formulate smart city strategies to ensure climate resilience as well as efficiency, sustainability and inclusiveness. This study has pursued an in-depth understanding on the best practices in smart city strategies of European countries in terms of climate resilience and digital innovation and compared these practices with those within the smart city strategy of Türkiye. This comparative study was conducted through secondary data analysis of smart city strategy documents. Climate resilience indicators were identified based on literature review and document analysis. Findings demonstrate that Türkiye's strategy promises several strengths to mitigate impacts of climate change. On the other hand, achieving the ambitious goals requires improved strategic integration considering the legislative actions, sustainable buildings as well as other strategic priorities such as citizen engagement for climate resilience. Climate resilience and other dimensions of resilience such as disasters and pandemics should be conceptualised and managed with a holistic perspective for more effective use of resources and integration.

Keywords: *Climate resilience, smart cities, technology, sustainability*

Introduction

Climate resilience at the city scale refers to the ability to proactively respond to changing environmental conditions and quickly recover from the negative effects of shocks triggered by extreme climate events (Schaefer et al., 2024). Climate resilience is often linked to acute events such as heat waves, heavy downpours, hurricanes, or wildfires that will occur more frequently or intensely as climate changes, but good resilience planning also concerns chronic events such as rising sea levels, worsening air quality, and population migration (C2ES, 2024).

In recent years, Türkiye has been susceptible to various disasters and extreme events due to destructive climate change impacts. Thus, within the framework of the '2020-2023 National

Smart Cities Strategy and Action Plan (2019)’, which was published by Republic of Türkiye Ministry of Environment, Urbanisation and Climate Change, climate resilience is highly valued considering different dimensions. Although several research investigated climate change issues from an urban perspective by considering digital technologies and the smart issue concept, there are limited studies that have addressed smart city strategic plans by carrying out a comparative approach focusing on climate resilience as a part of smart city initiatives. This study aims to delve into understanding the smart city strategy of Türkiye and compare it with the smart city strategies of other countries in Europe. Within this context, the main research questions of this study are as follows:

1- Is the smart city strategy of Türkiye incorporate a vision, strategies and targets for climate resilience?
2- What kind of recommendations can be made for Türkiye comparing it with smart city strategies of other countries to enhance climate resilience?

Methodology

This study follows 5 steps as shown in Figure 1. A literature review was followed by identification of climate resilience indicators. Then, secondary data analysis was carried out to compare smart city strategies followed by a discussion of findings and possible recommendations for Türkiye. Within the context of secondary data analysis, ‘2020-2023 National Smart Cities Strategy and Action Plan, Türkiye’ was compared with the smart city strategies of Germany, Norway, Switzerland, United Kingdom. These countries were selected for comparison, as they rank at the top globally, proving that they have achieved both their smart city and climate change resilience goals (IMD, 2023; Philips, 2024).

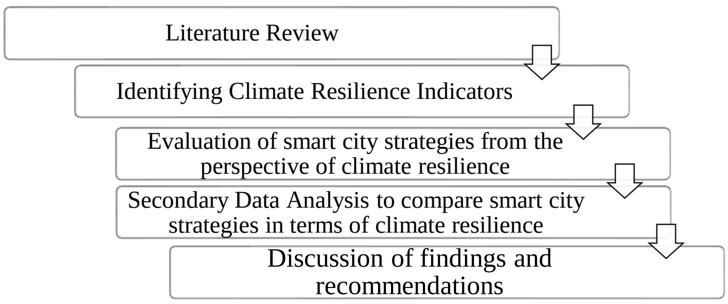

Figure 1: Research steps.

Literature Review

Smart city strategies have been developed in cities worldwide to boost the well-being of residents, social life and economic welfare through digital transformation and technology-based intervention (Tekin & Dikmen, 2024). In the literature, there is a growing interest in studies that have addressed the relation between climate resilience and smart cities. For example, García Fernández and Peek (2020) investigated the elements of adaptation to climate change in European Smart City initiatives to better understand to what extent smart cities can mitigate climate change impacts. Rajasekar et al. (2018) indicated some of the major problems with climate change mitigation, encountered by smart city initiatives and addressed some innovative solutions. After carrying out an exploratory field study and utilizing the urban climate resilience theoretical framework, Ahdekivi et al. (2023) argued that smart cities can leverage the potential of open data and citizen participation to achieve resilience to climate change. Huang-Lachmann (2019) sought to better understand policy implications and explore the synergies of climate change adaptation and smart cities. Pee and Pan (2022) addressed climate-intelligent cities and emphasized four information research issues as follows: development: energy and resource optimization, climate-neutral digital economy, digital citizen engagement, and intelligent governance. Chakravarty and Sarkar (2018) addressed how smart city is conceptualised in the literature and to determine the criteria which lead smart cities to have ability to formulate and succeed low carbon objectives. As a conclusion, it is apparent that climate resilience has been widely conceptualised as a part of smart city and to benefit from new technologies and implications of smart cities, some studies proposed different approaches to enable resilience.

Climate Resilience Indicators

Climate resilience is measured and evaluated in different aspects by different authorities worldwide. In reference to the International Monetary Fund, Climate Change Dashboard (2024), the indicators of climate change adaptation involve information on building financial and institutional resilience to deal with phenomena attributed to climate change. According to vision of United Nations Climate Change, Global Climate Action (2021), climate-risk driven actions around three pillars to be achieved are as follows: a) Urban resilience for better cities in terms of health, safety and thriving spaces that support resilient livelihoods and allow for green recovery post COVID-19, b) Rural resilience for ensuring agriculture supply chains are adaptive, equitable, and are equipped to adopt climate change, c) Coastal resilience for resilient coastal and riverine cities in terms of protecting natural ecosystems, livelihoods and economies. Thus, the climate resilience strategies should be multidimensional incorporating sustainability, health, safety, transport, equity; considering different components such as rural and coastal resilience as well as urban resilience which involve agricultural practices, supply chains, systems of finance and institutional structures enabling resilience. Different authorities implement strategies and reformulate their plans based on climate change implications. According to the European Regions Research and Innovation Network (2024), 100 climate-neutral and smart cities are targeted by 2030 within Cities Mission, including smart aspects, such as Positive Energy Districts, Digital Twins, the use of AI at local level, linking to the NetZeroCities Pilot City projects. Many cities around the world have also implemented smart city plans and achieved climate resilience targets. Stockholm is one of the cities that reduced CO_2 emissions by 25% per citizen since 1990 through strategies through different strategies (EC, 2017). In the next section, some findings from European countries will be listed to explore the strategies of climate change risk mitigation in cities.

Findings on Smart City Strategies

Table 1 shows the comparison of smart city strategies between Türkiye and selected European countries according to climate resilience indicators. 2020-2023 National Smart Cities Strategy and Action Plan, which was published by Ministry of Environment, Urbanisation and Climate Change (formerly known as Ministry of Environment and Urbanization) in 2019 was taken as a reference document for Turkish smart city strategy. Considering the regulations, institutional structures and finance in Europe, different financing schemes are allocated for the improvement of green infrastructure and energy-efficient projects. Legislative measures, especially those aimed at reducing CO_2 emissions, are planned to enable better climate resilience in Norway and Switzerland. In Germany, Climate and Transformation Fund and subsidies for energy-efficient buildings were introduced to support the climate resilience strategies. In Türkiye, IPA funding and other financial resources are allocated for municipal infrastructures and mechanism for cleaner production.

Table 1. Comparison of national smart city strategies.

Climate Resilience Indicators	Smart city strategies				
	Germany Smart City Charter (2017)	Norway Roadmap for smart and sustainable cities and communities in Norway (2019)	Switzerland Smart City Guide to the Implementation of Smart City Initiatives in Switzerland (Musiolik et al., 2020)	United Kingdom UK Smart Cities Directory (2020)	Türkiye 2020-2023 National Smart Cities Strategy and Action Plan (2019)
Regulations, finance and institutional structures	Supporting green infrastructure during the funding periods. Subsidies for energy-efficient buildings. Climate and Transformation Fund Funding for municipalities to enable energy-efficient buildings and renovations	Developing standards and regulations, which enable lower greenhouse emissions	Climate and energy policy requirements, such as reducing CO2 emissions Contractual cooperation between public authorities and the private sector to form a special-purpose entity.	Arranging funding for energy efficiency projects	Allocating Pre-Accession Assistance (IPA), EU funding for municipal infrastructures National and international financial resources and incentive mechanism for developing R&D and innovation capacity for cleaner production
Urban resilience	Climate-neutral and resource-efficient urban environment Promoting eco-friendly mobility, energy, heat, water, sewage and waste concepts Measures for climate-friendly urban development	Accelerating the 'green shift' Reducing the use of resources Ecofriendly choices Environmental friendly transport New energy solutions and more energy-efficient buildings	Resource- and environmental urban areas (buildings, public spaces, infrastructure systems) Promoting renewable energies, resource conservation Smart and sustainable buildings, urban development and planning Smart waste, smart lighting, combined mobility	Smart Energy- Smart grids, flexible energy distribution Renewable energy; Vehicle-to-Grid technology Smart buildings & housing Energy efficiency, high-performance buildings Integrated transport Environmental friendly smart mobility	Energy efficient and climate sensitive urban transportation strategies Best practices for environment-friendly parks, vertical gardens and roof gardens Creating a holistic information management system to increase information flow and sharing in national climate change studies. Smart energy networks
Rural and coastal resilience			Urban gardening	Geospatial analytics to prioritize investment, multiply asset value, optimize resources, and supercharge productivity in the water, agriculture, infrastructure, and forestry sectors Precision agriculture	Conservation of agricultural biodiversity and resources to adapt to the effects of climate change Carbon sequestration areas, such as pastures, forests and agricultural lands Less sea pollution
Climate change adaptation	Contributions to carbon-neutral, green and healthy municipalities Measures to sustainably enhance the energy efficiency of municipal supply systems - heating/cooling, water supply, wastewater disposal Measures in the areas of green infrastructure, sustainable mobility, and digitalization	Reducing greenhouse gas emissions and resource use in all areas of society Environmentally friendly energy and transport solutions Promoting circular economy and encouraging recycling and restoration of existing buildings. Easy choices for citizens to prefer climate-friendly solutions Clean air and water Access to green recreation areas	Air pollution monitoring	Hyperlocal environmental sensors meshes at city scale, which provide rich, real-time, actionable data to mitigate pollution. Dealing with noise issues Integrated sensors for environmental monitoring (CO2 levels, PM 2.5 levels, temperature, humidity) from both indoor and outdoor environments. Enhancing environmental quality and reducing the risk of litter clearance with AI. Intelligent traffic systems for better safety, efficiency, and the carbon footprint of transport environments. AI technology for environmental assessment	Managing surface water and groundwater systems through ensuring quality, necessary amount of water, and sustainability Waste management Green infrastructure Monitoring air quality through sensors. Regional clean air centers Soil management for less pollution, degradation and desertification. Soil rehabilitation and sustainable land management Biodiversity, ecosystem services, forestry policies Less CO2 emission, effective energy use, renewable energy Noise issues. noise maps Possible effects of climate change on drought Sensitivity and fragility analysis. Effects of temperature, precipitation, drought, flood and overflow. Hazard risk reduction systems Desertification and Erosion Risk Map
Citizen engagement	Citizen sensing, Sharing" and Crowd mapping Open workshops (FabLabs), hackathons, ideas competitions and think tanks	Physical and virtual platforms for determining problems and solutions.	Citizen participation to ensure that projects and processes have public support and are in line with the public's needs.	Smart citizens Citizen engagement Sustainability consultancy	Raising awareness for a sustainable and clean environment Stakeholder management

Türkiye revised Nationally Determined Contribution in 2023 by committing to a 41% reduction in greenhouse gas emissions by 2030 and intends to peak its emissions in 2038 at the latest and achieve net zero target by 2053 (UNDP, 2023). This commitment shows how seriously Türkiye takes the issue of greenhouse gas emissions. Due to Türkiye's old building stock, various measures need to be taken to achieve this goal. Therefore, new legal regulations that implement and control energy efficiency in buildings, positive energy districts and similar pilot projects, digital twins, artificial intelligence-based solutions can provide sustainable benefits in achieving emission targets.

Urban resilience which involves integrated management and sustainable use of resources are valued in different ways in Europe. Combined and environmental-friendly transport, easy and eco-friendly choices for society, sustainable and energy-efficient buildings by enabling more efficient use of heat, lightening and water, reducing the use of resources, and better waste management are the main goals within this indicator in Europe. Particularly, Smart Energy-Smart grids and Vehicle-to-Grid technology, mentioned in the UK smart city strategy, are promising innovative technologies for flexible energy distribution. Similar strategies, such as energy-efficient urban transportation, greening and smart energy networks also come to the fore in Türkiye. It is also planned to create a holistic information management system in order to increase information flow and sharing in national climate change studies. To ensure sustainable transportation, use of smart grid technologies may provide significant benefits.

The secondary data analysis indicated that rural and coastal resilience and climate-smart agricultural policies are rather limited within smart city strategy documents in Germany, Norway and Switzerland. But, this does not mean that those countries in Europe do not give importance to smart agriculture and food security. The German Federal Ministry of Food and Agriculture (Smart Agriculture, 2019) launched the "Digital Experimental Fields". Similarly, the Center for Precision Agriculture (2016) was established to boost technology in agriculture in Norway. On the other hand, UK smart city strategy points out precision agriculture, use of geospatial analytics for optimisation of financial resources and increasing productivity within the goals of climate-smart agricultural practices. In Türkiye, agricultural biodiversity and ability of agricultural lands for carbon sequestration are valued in national smart city strategy. In recent years, Türkiye has encountered problems with water and food security due to precipitation extremes and urban patterns. Precision agriculture, as Norway and UK well implemented, smart technologies and geospatial analysis could be beneficial for better agricultural productivity.

Climate change adaptation is another climate resilience indicator. Selected countries in Europe contribute to reducing greenhouse gas emissions, environmental-friendly mobility, circular economy, energy efficiency, heating/cooling, water supply, and water disposal at local levels. Hyperlocal environmental sensors for mitigating pollution and integrating sensors for environmental monitoring are the highlights of the UK national smart city strategy within this context. Similarly, Swiss smart strategy gives importance to air pollution monitoring. Dealing with noise issues, and environmental monitoring are also targeted. The research has shown that adapting climate change and risk reduction at local level is the most prominent issue of the Turkish smart city strategy document. Water management, monitoring air quality, soil management, biodiversity, CO2 emission, noise issues, and investigating deep impacts of temperature and precipitation extremes by considering desertification and erosion as well as preparing risk maps and initiating hazard risk reduction systems are comprehensively mentioned in the Turkish smart city document but needs more concrete actions, and use of digital technologies. Moreover, almost every region in Türkiye is under earthquake threat. A severe earthquake is expected in a very short time in Istanbul. Other countries, such as Greece, is also susceptible to similar complex risks and extreme events. Therefore, in counties like Greece and Türkiye, resilience strategies should integrate resilience to disasters such as earthquake as well as resilience to chronic events such as the climate change. European Commission encourages integration and implementation of national disaster risk plan and climate change strategy by designing and improving risk prevention and emergency preparedness as well as civil protection and comprehensive mechanism for the stakeholder coordination (EC, 2022). Thus, developing large scale alerting systems would be valuable both for mitigating climate change and being prepared for earthquake risks in Türkiye.

Citizen engagement plays an important role in achieving the desired level of climate resilience in smart city strategies in Europe. Physical and online sharing platforms, such as open workshops, and crowd mapping are planned to ensure collaboration with the public for new implementations and getting feedback about prospective actions. In Türkiye, raising awareness for a sustainable and clean environment as well as stakeholder management are the two important concerns of the national smart city strategy. To engage the society more into climate resilience targets, Türkiye should promote open sharing platforms and promote citizen sensing as highlighted in the German national smart city strategy.

Concluding Remarks

This research has investigated the smart city strategy of Türkiye, in the light of the practices in smart city strategies of other European countries in terms of both climate resilience and digital innovation. In general, Turkish smart city strategy promises several strengths to mitigate future impacts of climate change and enable climate resilience. The smart city strategy of Türkiye incorporates relevant climate resilience targets around the Europe, as the main strategies focus on reduction in CO2 emission, green infrastructure, energy-efficient transport, effective water management systems, food security, handling pollution and noise issues, and raising awareness about climate change. Despite the several pros of Turkish smart city strategy attributed to climate resilience, there are some issues, which need to be considered in detail for further improvements. New regulations that enforce energy efficiency in buildings through urban renewal and retrofitting the building envelope, integrated building services which enable waste heat recovery and less energy consumption would be useful for climate mitigation. In addition, smart grid- vehicle technologies and other smart solutions in transport systems, particularly in big cities, may contribute to less CO_2 emission. Due to precipitation extremes, water and food security is an important issue on the agenda of the smart city strategy of Türkiye. To ensure adequate water and agricultural productivity, this study has addressed precision agriculture, geospatial analysis and the use of smart technologies in agriculture and forestry. Türkiye has several strategies, which have focused on adaptation and risk reduction at local levels, however digital technologies could be better incorporated into the plans. Moreover, citizen engagement is a critical issue when environmental issues are discussed in Türkiye. Therefore, citizen sensing and open-sharing platforms may be good alternatives to increase the success of the national smart city strategy implementation and make people more engaged with climate resilience targets. This study aimed to present some of the findings from a comparative analysis of smart city strategies around Europe. The scope is limited to only four countries. Moreover, resilience as an integrated concept around several dimensions such as disasters, climate change and possible pandemics could not be captured due to investigation of only the smart city strategies ignoring possible strategies that may be a part of other documents such as the disaster emergency plans etc. Further research that includes more countries, and preferably a city- based approach would yield more representative and informative outputs. Despite this drawback, this study may contribute to smart city initiatives in Türkiye and similar countries by highlighting the need for a well-developed climate resilience strategy within smart city plans.

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References

Ahdekivi, V., Ghanbari, H., & Rossi, M. (2023). Building Climate Resilience in Smart Cities Using Open Data Services, *Proceedings of the 56th Hawaii International Conference on System Sciences*

C2ES, Center for Climate and Energy Solutions, Climate Resilience Portal. https://www.c2es.org/content/climate-resilience-overview/. (accessed on 5th May, 2024).

Center for Precision Agriculture (2016). https://www.nibio.no/en/about-eng/center-for-precision-agriculture (accessed on 28th April, 2024).

Chakravarty, D., & Sarkar, R. (2018). Conceptualising Indian Smart Cities: Criteria for Being Climate Resilient. *Working Paper Series.*

EC, European Commission (2017). The making of a smart city: best practices across Europe https://smart-cities-marketplace.ec.europa.eu/sites/default/files/2021-04/the_making_of_a_smart_city_-_best_practices_across_europe.pdf (accessed on 12th May, 2024).

EC, European Commission (2022). https://reform-support.ec.europa.eu/what-we-do/green-transition/supporting-greece-tackling-natural-and-environmental-disasters_en. (accessed on 13th May, 2024).

European Regions Research and Innovation Network (2024), https://errin.eu/sites/default/files/2024-02/Smart%20Cities%20Annual%20Plan%202024_0.pdf (accessed on 12th May, 2024).

García Fernández, C., & Peek, D. (2020). Smart and sustainable? Positioning adaptation to climate change in the European smart city. *Smart Cities*, 3(2), 511-526.

Huang-Lachmann, J. T. (2019). Systematic review of smart cities and climate change adaptation. *Sustainability Accounting, Management and Policy Journal*, 10(4), 745-772.

IMD World Competitiveness Center Smart City Index Report (2023). Available online: https://www.imd.org/wp-content/uploads/2023/04/smartcityindex-2023-v7.pdf (accessed on 18th June 2023).

International Monetary Fund, Climate Change Dashboard https://climatedata.imf.org/pages/adaptation. (accessed on 28th April, 2024).

Musiolik, J., Kohler, A., Vögeli, P., Lobsiger-Kägi, E., Müller, L. and Carabias- Hütter, V. (2020). Smart City: Guide to the Implementation of Smart City Initiatives in Switzerland. *Bern: Swiss Federal Office of Energy.*

National Smart Cities Strategy and Action Plan (2019). https://akillisehirler.gov.tr/wp-content/uploads/EylemPlani.pdf (accessed on 10th November 2023).

Pee, L. G., & Pan, S. L. (2022). Climate-intelligent cities and resilient urbanisation: Challenges and opportunities for information research. *International Journal of Information Management*, 63, 102446.

Philips C. (2024). Which Countries Are Best Prepared for the Impacts of Climate Change? Henley and Partners. Available on https://www.henleyglobal.com/publications/investment-migration-climate-resilience-index/investor-insights/which-countries-are-best-prepared-impacts-climate-change. (accessed on 26th April 2024).

Rajasekar, U., Chakraborty, S., & Bhat, G. (2018). Climate resilient smart cities: opportunities for innovative solutions in India. Climate Change in Cities: *Innovations in Multi-Level Governance*, 203-227.

Roadmap for smart and sustainable cities and communities in Norway (2019). https://doga.no/globalassets/pdf/smartby-veikart-19x23cm-eng-v1_delt.pdf. (accessed on 26th April 2024).

Smart Agriculture (2019) https://smart-agriculture.org/industry-and-research/experimental-fields. (accessed on 28th April 2024).

Smart City Charter (2017), building-housing/city-housing/smart-city-charter short.html;jsessionid=FC811DE332255C02BF961E44848814E6.live882. (accessed on 26th April 2024).

Schaefer, M., Thinh, N. X., & Greiving, S. (2020). How can climate resilience be measured and visualized? Assessing a vague concept using GIS-based fuzzy logic. *Sustainability*, 12(2), 635.

Tekin, H., & Dikmen, I. (2024). Inclusive smart cities: an exploratory study on the London smart city strategy. *Buildings*, 14(2), 485.

UK United Kingdom Smart Cities Directory, (2020) https://eu.eventscloud.com/file_uploads/2ed36ce5867a41381abc8a5861b7fcd7_UKSmartCitiesDirectory.pdf (accessed on 26th April 2024)

United Nations Climate Change, Global Climate Action (2021), https://unfccc.int/sites/default/files/resource/Resilience_Vision%26Summary.pdf, (accessed on 5th May, 2024).

UNDP, United Nations Development Programme, https://climatepromise.undp.org/what-we-do/where-we work/Türkiye#:~:text=T%C3%BCrkiye's%20revised%20NDC%20commits%20to,achieve%20net%20zero%20by%202053. (accessed on 13th May, 2024).

Managing Ambiguity in Construction Projects in Nigeria: The case for Selecting and Achieving Set Milestones

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Abstract

Investigations that explore the knowledge, selection, and influence of milestone management practices on the performance of construction projects are limited. This study examined the dynamics involved in managing ambiguity and achieving set milestones in construction projects in Minna, Nigeria. Using the quantitative method, questionnaires (n = 150) were distributed to obtain data from construction professionals who adopted milestone management practices on their projects, of which 119 responded. This resulted in a remarkable 79% response rate, and high data reliability (0.962) was obtained. Notably, the findings underscore the pivotal role of specific milestone selection criteria in building construction projects as identified and ranked by the respondents. Scope of work (0.861) ranked first; schedule estimation (0.845) and quality assurance (0.845) ranked second; budget significance (0.844) and resource allocation (0.844) ranked third. Further findings show a significant relationship (i.e., p-value = 0.00) between the dynamics of milestone management and the performance of projects. The study accentuates the urgent need for appropriate selection and management of milestones for timely project completion in Nigeria. With this widely known practice, construction professionals would be able to represent and manage work activities and achieve set time expectations regardless of project disruptions.

Keywords: *construction, milestones, planning, professionals, project, time.*

Introduction

Construction projects often deviate from their planned trajectory, posing challenges for project managers striving to align activities with contractual time expectations. Given the capital-intensive nature of construction projects and clients' desires for timely completion, professionals often rely on project milestones to manage deviations from the plan. Numerous authors (Globerson et al., 2016; Olubajo et al., 2019; Orekan & Babatunde, 2020; Olugboyega & Windapo, 2022) have conceptualized milestones differently in the literature, ranging from clear targets set in a project, designated payment times, project segments, work packages, to project phases, highlighting the diverse perspectives on their nature and function. The literature on construction management typically discusses milestones in two main themes. A study by Altahtooh and Alaskar (2018) focus on factors determining the size or content of milestones, while Scarbrough et al. (2012) view milestones as representations of time or work in a project. However, limited research delves into how professionals manage ambiguity in projects using milestones. This study aims to explore the dynamic relationship involved in managing ambiguity in selecting and achieving milestones in projects in Minna, Nigeria. Specifically, it seeks to examine the relationship between the level of knowledge and practice of milestone management and the influence of milestone management practices on construction time performance. The study presents the following hypotheses to test these relationships:

H0: There is no relationship between level of knowledge and the level of adoption of milestone management.
H1: There is a relationship between level of knowledge and level of adoption of milestone management
H0: There is no relationship between level of adoption of milestone management and time performance.
H1: There is a relationship between level of adoption of milestone management and time performance.

Literature Review

The literature on milestones not only delves into the factors influencing their creation but also highlights their role as representations of work packages or time. Scarbrough et al. (2012) investigated the use of milestone programmes in the context of computer game production. They explored how milestone programmes facilitated product design work across various developer groups. The authors argued that milestone programmes aid in coordinating the practices of different developer groups within time-constrained processes, particularly in managing emergent conditions. According to literature on milestones, various factors influence the size or content of work within them across different projects. For instance, Globerson et al. (2016) surveyed project managers to identify criteria determining the work content or size of project milestones and found organizational unit responsibility role in clear assignment of responsibilities. Additionally, Altahtooh and Alaskar (2018) explored the relationship between milestones and decision-making structures across projects, highlighting factors such as end phase or task, zero duration, and deliverables as commonly associated with milestones. Meanwhile, Sunmola (2020) investigated factors influencing milestone creation in IT projects, identifying conformance to requirements, deadlines, and time-to-market as primary considerations.

Implementing Key Performance Indicators (KPIs) and regular performance assessments, as recommended by Adabre et al. (2023), facilitates progress monitoring and allows for adjustments as needed. Thus, highlighting the importance of milestone management. Proactive risk assessment and mitigation strategies, as emphasized by Boateng et al. (2022) ensure timely identification and addressing of potential setbacks. Implementing quality control checks at milestone points, as suggested by Miranda (2019) and Altahtooh and Alaskar (2018), helps maintain construction quality and prevents rework and delays. These practices are essential for successful project completion within schedule and budget constraints. Sunmola (2020) expressed that effective project planning and scheduling, is foundational to milestone management and involves creating detailed timelines, identifying critical milestones, and efficient resource allocation. Time performance indicators are essential for evaluating the progress of construction projects, encompassing seven key aspects: predictability of time, quick start, quick progress, quick finish, slow start, slow progress and slow finish (Gledson et al., 2018). These indicators play a vital role in project success. A quick start, quick progress, and quick finish are desirable outcomes, while slow counterparts can lead to delays and additional costs.

In summary, project planning, monitoring, and risk management are crucial for ensuring predictability and time performance in construction projects. The above studies collectively focus on a relationship between various project factors and milestones, emphasizing the importance of payment systems, responsibility assignment, and deadlines in milestones. However, they overlook the dynamics relationship between the level of knowledge, selection and adoption of milestone management in managing ambiguity and achieving set milestones.

Research Method

This research utilizes a descriptive survey approach to investigate the intricacies of managing and achieving predetermined milestones in projects characterized by ambiguity, focusing specifically on Minna, Niger State (Figure 1), Nigeria. Minna is situated in Niger State, located in the North-Central geopolitical zone of Nigeria (Figure 2). It is positioned between specific latitude 8020" and 11020" North and longitude 3040" and 7040" East. Data for the study was gathered through well-designed questionnaires distributed among construction professionals actively involved in milestone management on their projects. The study used a sample size of 150 respondents, with 119 filling out and returning the questionnaires, yielding a response rate of 79.3%. This response rate was excellent and sufficient to draw conclusions for the study.

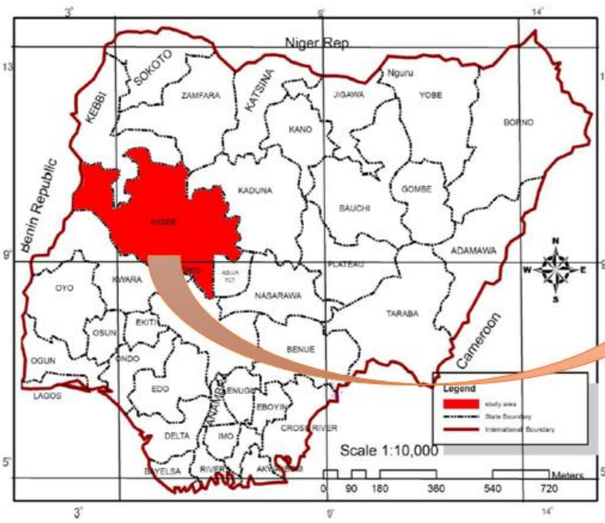

Figure 1: Map of Nigeria showing Niger State.

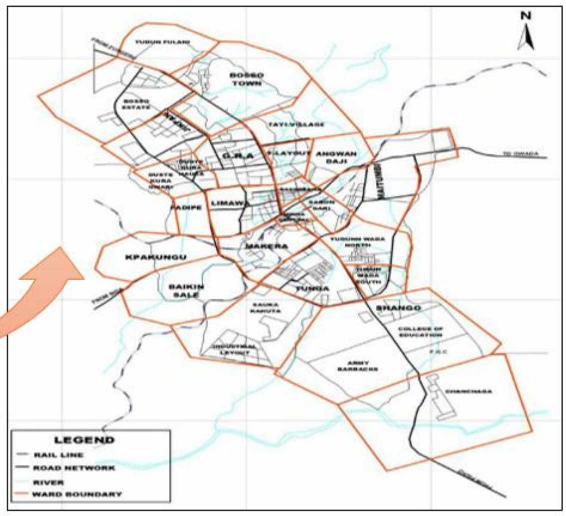

Figure 2: Map of Minna.

The survey encompassed inquiries pertaining to milestone management practices, criteria for milestone selection, and indicators of time performance. Utilizing a five-point Likert scale, respondents were prompted to assess the importance, level of knowledge, level of adoption, and various time performance indicators associated with milestone management. Statistical analysis of the collected data involved computing mean item scores and employing the Relative Importance Index (RII) method and correlations between milestone management practices and the time performance outcomes of construction projects.

Results and Discussion

Table 1 provides an overview of the characteristics of the study participants. It reveals that 16% of the respondents hold positions as contractors, 23.5% as construction managers, 24.4% as site managers, 8.4% as operational managers, and 27.7% in various other roles within their companies. Professionally, the majority identify as builders (61.3%), followed by quantity surveyors (18.8%), engineers (10.1%), and architects (5.9%). In terms of educational background, 47.1% of respondents hold B. Tech/B.Sc. degrees, 25.2% have second degrees, 10.1% are HND graduates, and 6.7% have PhDs. Professionally, 52.1% are associated with NIOB, 16.8% with NIQS, 10.9% with NIA, 7.6% with COREN, and 12.6% with other professions. Regarding experience, 31.9% have less than 5 years, 29.4% have 10 years, 26.1% have 15 years, and 12.6% have 20 years or more. Gender-wise, 81.5% of participants are male and 18.5% are female. Additionally, 59.7% have worked on projects for 0-5 years, 19.3% for 5-10 years, 10.1% for 11-15 years, 5.9% for 16-20 years, and 5.0% for over 20 years.

Table 1. Characteristics of respondents.

Characteristics	Description	Freq.	%
Role/position in your firm	Contract/Cost Manager	19	16
	Operations manager	10	8.4
	Project manager	33	27.7
	Construction manager	28	23.5
	Site manager	29	24.4
	Total	119	100
Work experience (Construction)	1 – 5	38	31.9
	6 – 10	35	29.4
	11 - 15	31	26.1
	16 – 20	10	9.17
	21 & above	5	4.58
	Total	119	100
How long working at your firm (in years)	1 – 5	71	59.7
	6 - 10	23	19.3
	11 - 15	12	10.1
	16 – 20	7	5.9
	21 & above	6	5.0
	Total	119	100
Highest Qualification	PhD	8	6.7
	MSc./MTech.	30	25.2
	BSc./BTech.	56	47.1
	HND	12	10.1
	OND	13	10.9
	Total	109	100
Gender	Male	87	79.82
	Female	22	20.18
	Total	119	100
Professional Background	Architect	5	5.9
	Builder	73	61.3
	Engineer	12	10.1
	Quantity Surveyor	20	18.8

Surveyor	7	5.9
Total	119	100

Relative importance index was used to examine and identify the critical milestone selection criteria in building construction projects and to rank each variable according to their importance. From Table 2, the critical milestone selection criteria as identified are: Scope of work was ranked first, Schedule estimation and Quality assurance were ranked second, Budget significance and Resource allocation were ranked third, cost estimation was ranked fourth, while client expectations were ranked fifth.

Table 2. Ranking of milestone selection criteria in construction projects.

Milestone selection criteria	Total weight	RII	Ranking
Project Complexity and scope	482	0.810	9
Critical path analysis	468	0.787	13
Project phases and key deliverables	475	0.798	11
Time based	491	0.825	7
Budget significance	502	0.844	3
Quality Assurance	503	0.845	2
Risk mitigation	471	0.792	12
Stakeholders communication	463	0.778	15
Resource allocation	502	0.844	3
Regulatory compliance	490	0.824	8
Client expectations	496	0.834	5
Organizational unit	465	0.782	14
Cost estimation	500	0.840	4
Schedule estimation	503	0.845	2
Deliverable basis	481	0.808	10
Scope of work	512	0.861	1
Risk management	495	0.832	6

Table 3 presents the respondents' knowledge levels on various milestone management practices. In project planning and scheduling, 41.2% demonstrate adequate knowledge, with 6.7% showing superior understanding, 26.1% having basic knowledge, 21% minimal knowledge, and 5% having very minimal to no knowledge, resulting in a mean value of 3.24, indicating a basic level of knowledge. Concerning the identification of critical paths, 37% exhibit adequate knowledge, 5.9% possess superior understanding, 23.5% have basic knowledge, 27.7% minimal knowledge, and only 5.9% very minimal to no knowledge, yielding a mean value of 3.09, also indicating a basic level of knowledge. In resource allocation, 41.2% showcase adequate knowledge, 15.1% have superior understanding, 21.8% basic knowledge, 18.5% minimal knowledge, and only 3.4% very minimal to no knowledge, resulting in a mean value of 3.46, indicating adequate knowledge in this aspect.

Table 3. Level of knowledge of milestone management.

Milestone management practices	V.M.K.	M.K	BK	A.K.	S.K	MIS	Rank
Planning & scheduling	6	25	31	49	8	3.24	6th
Indentification of critial path	7	33	28	44	7	3.09	7th
Resource allocation	4	22	26	49	18	3.50	4th

Regular monitoring & reporting	3	15	28	51	22	3.62	2nd
Communication & collaboration	4	10	27	52	26	3.72	1st
Control measures	4	19	22	57	17	3.54	3rd
Stakeholder involvement	6	23	27	45	18	3.39	5th

V.M.K.-Very minimal knowledge, M.K. - Minimal knowledge, B.K-Basic knowledge, A.K.-Adequate knowledge, S.K.-Superior knowledge

In terms of regular monitoring and reporting, 23.5% of respondents demonstrate adequate knowledge, with 18.5% showing superior understanding, 23.5% having basic knowledge, 12.6% minimal knowledge, and only 2.5% very minimal to no knowledge, resulting in a mean value of 3.62, indicating adequate knowledge. Regarding communication and collaboration, 43.7% exhibit adequate knowledge, 21.8% possess superior understanding, 22.7% basic knowledge, 8.4% minimal knowledge, and only 3.4% very minimal to no knowledge, yielding a mean value of 3.72, indicating adequate knowledge. In terms of control measures, 47.9% showcase adequate knowledge, 14.3% have superior understanding, 18.5% basic knowledge, 16% minimal knowledge, and only 3.4% very minimal to no knowledge, resulting in a mean value of 3.54, indicating adequate knowledge. Lastly, for stakeholder involvement, 37.8% demonstrate adequate knowledge, 15.1% possess superior understanding, 22.7% basic knowledge, 19.3% minimal knowledge, and only 9% very minimal to no knowledge, resulting in a mean value of 3.39, indicating a basic level of knowledge.

From Table 4, it's evident that respondents commonly adopt milestone management practices across various aspects. In project planning and scheduling, 36.1% often adopt these practices, with 27.7% always adopting them, resulting in a mean value of 3.66, indicating frequent adoption. Similarly, for identifying critical paths, 36.1% often adopt them, with 21% always adopting, yielding a mean value of 3.55, suggesting common adoption. Regarding resource allocation, 35.3% always adopt, and 31.9% often adopt, with a mean value of 3.8, indicating prevalent adoption. For regular monitoring and reporting, 44.5% always adopt, and 26.1% often adopt, resulting in a mean value of 3.92, indicating widespread adoption. In communication and collaboration, 36.1% always adopt, and 31.1% often adopt, with a mean value of 3.82, suggesting common adoption. Concerning control measures, 27.7% always adopt, and 34.5% often adopt, yielding a mean value of 3.63, indicating frequent adoption. Finally, for stakeholder involvement, 27.7% always adopt, and 29.4% often adopt, with a mean value of 3.55, indicating common adoption.

Table 4. Level of adoption of milestone management on projects.

Milestone management practices	Never	Rarely	Sometimes	Often	Always	MIS	Rank
Planning & scheduling	9	13	21	43	33	3.66	6th
Indentification of critial path	4	20	27	43	25	3.55	7th
Resource allocation	8	11	20	38	42	3.80	4th
Regular monitoring & reporting	8	11	16	31	53	3.92	2nd
Communication & collaboration	8	10	21	37	43	3.82	1st
Control measures	11	10	24	41	33	3.63	3rd
Stakeholder involvement	11	14	26	35	33	3.55	5th

The study aimed to determine whether there exists a relationship between the level of knowledge of milestones and the level of adoption of milestones, with a significance level of α=0.05. Hypotheses were formulated: H0 (no relationship) and H1 (a relationship). Results from Table 5 indicate a positive and significant relationship between the two variables. This suggests that as knowledge of milestone management practices increases, so does the level of adoption. This finding aligns with previous research by Song et al. (2009) where knowledge influenced the development of plans.

Table 5. Correlation between the level of knowledge and the practice of milestone management.

Level of Knowledge/Adoption of Milestone management	N	R -V	P - V	Decision
Level of knowledge of planning & Scheduling Level of adoption of planning & Scheduling	119	0.582	0.000	Accept
Level of knowledge in identification of critical path Level of adoption in identification of critical path	119	0.544	0.000	Accept
Level of knowledge of resource allocation Level of adoption of resource allocation	119	0.655	0.000	Accept
Level of knowledge of regular monitoring & reporting Level of adoption of regular monitoring & reporting	119	0.544	0.000	Accept
Level of knowledge of communication & collaboration Level of adoption of communication & collaboration	119	0.429	0.000	Accept
Level of knowledge of control measure Level of adoption of control measure	119	0.485	0.000	Accept
Level of knowledge of stakeholder involvement Level of adoption of stakeholder involvement	119	0.500	0.000	Accept

The study aimed to investigate the relationship between the level of adoption of milestone management and time performance, with a significance level of α=0.05. Hypotheses were formulated: H0 (no relationship) and H1 (a relationship). Results from Table 6 indicate a significant relationship between the level of adoption of milestones and time predictability. The correlation coefficients ranged between 0.382 and 0.480, with a p-value of 0.000, which is less than 0.05, indicating statistical significance. This finding is consistent with previous research by Idoro (2009), which highlighted the significant influence of planning level on delivery time.

Table 6. Level of adoption of milestone management and time performance.

Correlation of milestone management and time performance	N	R -V	P- V	Decision
Level of adoption of planning & Scheduling				
Predictability of time	119	0.383	0.000	Accept
Quick start	119	0.358	0.000	Accept
Slow start	119	0.268	0.000	Accept
Quick progression	119	0.390	0.000	Accept
Slow progression	119	0.175	0.057	Reject
Quick finish	119	0.321	0.000	Accept
Slow finish	119	0.268	0.003	Accept
Level in identification of critical path				

Predictability of time	119	0.484	0.000	Accept
Quick start	119	0.285	0.002	Accept
Slow start	119	0.257	0.005	Accept
Quick progression	119	0.387	0.000	Accept
Slow progression	119	0.283	0.002	Accept
Quick finish	119	0.375	0.000	Accept
Slow finish	119	0.265	0.004	Accept
Level of resource allocation				
Predictability of time	119	0.409	0.000	Accept
Quick start	119	0.350	0.000	Accept
Slow start	119	0.288	0.001	Accept
Quick progression	119	0.342	0.000	Accept
Slow progression	119	0.199	0.030	Accept
Quick finish	119	0.224	0.014	Accept
Slow finish	119	0.220	0.016	Accept
Level of regular monitoring & reporting				
Predictability of time	119	0.386	0.000	Accept
Quick start	119	0.316	0.000	Accept
Slow start	119	0.230	0.012	Accept
Quick progression	119	0.429	0.000	Accept
Slow progression	119	0.200	0.029	Accept
Quick finish	119	0.312	0.001	Accept
Slow finish	119	0.234	0.011	Accept
Level of communication & collaboration				
Predictability of time	119	0.424	0.000	Accept
Quick start	119	0.211	0.021	Accept
Slow start	119	0.281	0.002	Accept
Quick progression	119	0.397	0.000	Accept
Slow progression	119	0.239	0.009	Accept
Quick finish	119	0.290	0.001	Accept
Slow finish	119	0.265	0.004	Accept
Level of control measure				
Predictability of time	119	0.430	0.000	Accept
Quick start	119	0.375	0.000	Accept
Slow start	119	0.208	0.023	Accept
Quick progression	119	0.400	0.000	Accept
Slow progression	119	0.186	0.043	Accept
Quick finish	119	0.370	0.001	Accept
Slow finish	119	0.163	0.077	Reject
Level of stakeholder involvement				
Predictability of time	119	0.407	0.000	Accept
Quick start	119	0.282	0.002	Accept
Slow start	119	0.373	0.000	Accept
Quick progression	119	0.281	0.002	Accept
Slow progression	119	0.252	0.006	Accept
Quick finish	119	0.202	0.028	Accept
Slow finish	119	0.345	0.000	Accept

The analysis revealed a positive correlation between the level of adoption of milestone management practices and project time predictability. Significant relationships were observed between adoption levels and quick project starts, suggesting that higher adoption leads to improved time performance during project initiation (Gledson et al., 2018). Increased adoption levels across various aspects of milestone management, including project planning, critical path identification, resource allocation, monitoring and reporting, communication, collaboration, control measures, and stakeholder involvement, were associated with quicker project progression, as indicated by significant p-values below 0.05. However, while project planning and scheduling had an insignificant relationship with slow progression, other factors like critical path identification, resource allocation, monitoring and reporting, communication, collaboration, and stakeholder involvement showed significant positive relationships with slow progression. Similarly, control measures exhibited an insignificant relationship with slow finishes, whereas project planning, critical path identification, resource allocation, monitoring and reporting, communication, collaboration, and stakeholder involvement all had significant positive relationships, suggesting that higher adoption levels of these practices increase the likelihood of experiencing slow project finishes.

Conclusion

The aim of this study was to examine the dynamic relationship involved in managing ambiguity in selecting and achieving set milestones in construction projects in Minna, Nigeria. The study argues that selecting and managing milestones is widely known practice that enables professionals to represent and manage work activities to achieve set expectations of time regardless of project disruptions.

References

Adabre, M. A., Chan, A. P., & Edwards, D. J. (2023). Modeling relationship between success factors (policies) and critical success criteria (goals) for sustainable housing in developing countries. *International Journal of Construction Management*, *23*(10), 1642-1652.

Altahtooh, U., & Alaskar, T. (2018). Understanding relationship between milestone and decision-making in project management: a qualitative study among project managers in Saudi Arabia. *International Journal of Business Management*, *13*, 184.

Assaf, S. A., & Al-Hejji, S. (2006). Causes of delay in large construction projects. *International Journal of Project Management*, *24*(4), 349-357.

Boateng, A., Ameyaw, C., & Mensah, S. (2022). Assessment of systematic risk management practices on building construction projects in Ghana. *International Journal of Construction Management*, *22*(16), 3128-3136.

Gledson, B., Williams, D., & Littlemore, M. (2018). Construction planning efficiency and delivery time performance: analysing failure in task-level ‘hit rates’.

Globerson, S., Vardi, S., & Cohen, I. (2016). Identifying the criteria used for establishing work package size for project WBS. *Journal of Modern Project Management*, *4*(1), 173-173.

Idoro, G. (2009). Evaluating levels of project planning and their effects on performance in the Nigerian construction industry. *Construction Economics and Building*, *9*(2), 39-50.

Miranda, E. (2019). *Milestone planning: a participatory and visual approach 1, 2*.

Olubajo, O., Hughes, W., & Schweber, L. (2019). Construction programmes and programming: a critical review. *Proceedings of 10th Nordic Conference on Construction Economics and Organization*.

Olugboyega, O., & Windapo, A. (2022). Investigating the strategic planning of BIM adoption on construction projects in a developing country. *Journal of Construction in Developing Countries*, *27*(2), 183-204.

Orekan, A. A., & Babatunde, O. (2020). Evaluation of the impact of building artisans on residential housing delivery in Mupin Town, Ado-Odo/Ota Local Government, Ogun State.

Song, L., Mohamed, Y., & AbouRizk, S. M. (2009). Early contractor involvement in design and its impact on construction schedule performance. *Journal of Management in Engineering*, *25*(1), 12-20.

Sunmola, H. O. (2020). Evaluation of motivating and requiring factors for milestones in IT projects. *Procedia Manufacturing*, *51*, 1469-1477.

Circular Economy Risks in Construction Projects and Digital Technologies

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Abstract

Construction projects are long-term investments with significant impacts on the economy, environment, and society throughout their life cycle. Recently, circular economy practices have been implemented to address the resource-intensive nature of construction projects with several challenges due to their size and complexity. Meanwhile, various digital technologies, such as augmented reality, digital twins, BIM, GIS, IoT, RFID, etc., are utilized in the construction sector to facilitate a smooth transition to circular economy business models. The current literature lacks a comprehensive study on which digital technologies have the most potential to mitigate uncertainties during the integration of circular economy principles in construction projects. Together with these, the purpose of this study is to identify interactions among the risks associated with circular economy practices and digital technologies. For this purpose, circular economy risks and digital technologies utilized in circularity principles are identified through a comprehensive literature review. An interaction matrix is constructed based on the potential contributions of digitalization technologies in circular practices to present the most appropriate technologies for mitigating risks. The developed interaction matrix provides a preliminary guideline on the application of circular practices from the risk management perspective.

Keywords: *circular economy, construction risk management, digital technologies.*

Introduction

Construction projects have significant impacts on the economy, environment and society. For example, they contribute 13% of gross domestic product (Silva et al., 2015) in terms of the economic aspect. Besides, 35% of global CO_2 emissions, 45%-65% of the waste deposited in landfills, 30% of greenhouse gases are generated from construction projects considering their environmental impacts (Lima et al., 2021). Construction projects also cause displacement, resettlement, change in access to productive resources, and loss of livelihood opportunities to the local society (Phelan & Dawes, 2013). The current construction management practices mostly utilize a linear economy based on a take-make-dispose approach (Sariatli, 2017). According to Guerra et al. (2021), integrating a circular economy can reduce waste and save $100 billion per year by enhancing construction productivity. Nowadays, there is a paradigm shift from a linear economy to a circular economy in the construction sector which has established the idea of recycle-reuse-regenerate principles (Norouzi et al., 2021). On the other hand, the transition from a linear to circular economy model includes some challenges that may lead to uncertainties in decision-making, supply chain, design issues during the implementation phase as it is a new process for the construction sector (Kazancioglu et al., 2023). Recently, digital technologies such as big data, artificial intelligence, blockchain and internet of things (IoT) are promising for the transition towards circular economy business models in construction sector by addressing the barriers confronted during the implementation (Chauhan et al., 2022). Considering these, the purpose of this study is to identify interactions between circular economy risks and digital technologies. For this purpose, the research questions (RQ) listed below will be addressed in the forthcoming sections of this paper:

> *(RQ.1)* What are the circular economy risks in construction projects identified in the current literature?
> *(RQ.2)* What are the digital technologies utilized in circularity practices in construction projects?
> *(RQ.3)* Which digital technologies can address circular economy risks in construction projects?

This study conducts a literature review to analyze the circular economy risks in construction projects and the role of digital technologies in circular economy practices. After identifying the circular economy risks and relevant digital technologies, the study presents the interactions between these risks and technologies in an interaction matrix.

Background

A circular economy is a business model based on effective planning of refusing, rethinking and reducing resources that do not create value by aiming for zero waste and pollution (Guerra et al., 2021) and it has been gaining interest since the 1970s (Geissdoerfer et al., 2017). The circular economy principles include minimizing the waste creation, enhancing resource resumption, promoting the utilization of recycled materials, effectively managing material flow to promote environmental, economic, and societal well-being, and improving innovation (Jahan et al., 2022). The implementation areas of the circular economy principles in the built environment are mentioned as design for disassembly, design for modularity, determination of reusable and recyclable materials, design for manufacturing, material banks, integration of efficient processes, waste as a resource, resources data management, resources reverse logistics, adaptive reuse and repurposing (Guerra et al., 2021). Strategies for the integration of circular economy principles in the design phase are listed as adaptability, flexibility, durability, change, disassembly, deconstruction, dismantling, demountability, recycling, reuse and waste consideration (Figueirôa, 2023). In summary, the integration of circular economy principles can enhance the efficiency and health of the built environment (Çimen, 2021).

Recent developments in Industry 4.0 enable the construction industry to integrate several digital technologies such as Augmented Reality (AR), Virtual Reality (VR), Building Information Modeling (BIM), Unmanned Aerial Vehicles (UAVs), Internet of Things (IoT), robotics, big data and analytics (Tung et al., 2021; Statsenko et al., 2023). Digitalization has the potential not only for the optimization of overall project performance but also to facilitate the transition to a more circular economy. The nature of construction projects is complex and unique and also requires the involvement of different stakeholders (Rostami & Oduoza, 2017). There are numerous key performance indicators for construction projects such as time, cost, quality, productivity, Experience Modification Rate (EMR), change orders, environmental, economic, and social impact, and stakeholder satisfaction (Chan & Chan, 2004). Nevertheless, construction projects are still facing various project performance issues like delays, conflicts, productivity loss, lack of coordination and high amount of waste (Tariq & Gardezi, 2023). Subsequently, digitalization and circular economy have the potential to address these challenges. For instance, Parusheva (2019) mentions the advantages of digitization in terms of increased productivity, accelerating schedule, and optimization of project duration. Additionally, Antikainen et al. (2018) list the benefits of digitalization in a circular economy as more closed material loops, access to reliable information for material availability, location and condition, and minimization of waste and transaction costs.

In summary, the integration of circular economy principles enables the utilization of resources efficiently and reduces waste generation from construction projects. Thus, it is important to address risks in circular economy principles to get the maximum benefit from their implementation. Recent digital technologies have the potential to address risks confronted in circular economy implementation by offering more efficient, safe, optimized, remote and automated practices in the construction sector.

Research Methodology

The research methodology of this study involves a two-step literature review using the Scopus and Web of Science databases. The review considers articles, conference papers, book chapters, and theses/dissertations focused on circular economy and risk management in the field of construction management. The search is limited to the English language with a focus on the last decade to scrutinize the most recent studies considering the recent technological developments and evolution of the circular economy concepts. The flowchart for the research methodology is given in Figure 1.

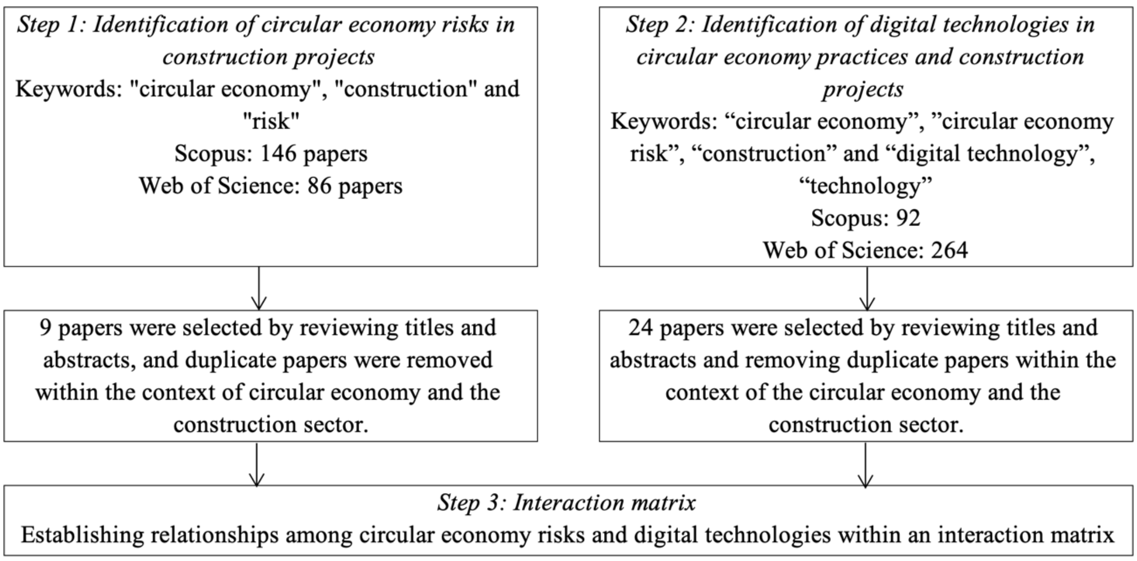

Figure 1: Flowchart of the research methodology.

Results and Discussion

In the first step, 20 circular economy risks are identified and listed, which are presented in Table 1 with the reference studies.

Table 1. Identified circular economy risks in construction projects.

ID #	*Circular Economy Risks*	*References*								
		A	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*
R.1	Lack of policies, laws, support and guidelines	*				*	*		*	*
R.2	Lack of awareness, knowledge and interest	*				*	*	*		*
R.3	Time consuming and labor-intensive procedure	*					*	*		
R.4	Lack of information sharing and decision-making					*	*	*		*
R.5	Poor inventory management									*
R.6	High investment cost and funding issues	*				*		*	*	*
R.7	Financial instability	*				*			*	*
R.8	Procurement cost					*				
R.9	Lack of standardization							*		
R.10	Improper circular design				*					*
R.11	Improper reusable material/waste identification	*								
R.12	Presence of hazardous material in waste		*	*						
R.13	Availability of circular materials						*			
R.14	Circular material life cycle and revenue						*		*	*
R.15	Recovered material quality issues	*					*	*	*	*
R.16	Improper safe recovery processes	*			*	*	*			*
R.17	Ineffective material tracking	*			*					*
R.18	Ineffective transportation route management	*							*	
R.19	Improper fleet selection	*								
R.20	Material delay/supplier risk						*		*	

Note. Reference sources are A: Dulia et al, 2021; B: Wu et al., 2021; C: Cook et al., 2022; D: Cuvelier et al., 2022; E: AlMashaqbeh & Hernandez, 2023; F: Hassan et al., 2023; G: Kazancoglu et al., 2023; H: Tuni et al., 2023; I: Wuni & Abankwa, 2023.

In the second step, digital technologies utilized in circular economy principles were identified. Overall, 13 digital technologies were extracted from the literature, and the identified digital technologies in the context of circular economy practices are given with reference studies in Table 2.

Additive manufacturing enhances the utilization of reusable resources efficiently (Çetin et al., 2021). Artificial intelligence can optimize material and waste categorization (Oluleye et al., 2023). Big data enhances the project management and decision-making processes in the circular economy Chi et al., 2023). Blockchain offers transparency and tracking of materials and wastes (Hristova, 2022). Building Information Modelling enables construction practitioners to see building circularity and track material data (Behún & Behúnová, 2023). Digital platforms improve information sharing among stakeholders (Kovacic et al., 2020). Digital twins ease the remanufacturing processes by considering material and waste management (Elghaish et al., 2022). The utilization of drones optimizes the tracking of materials, wastes and work progress (Setaki & Timmeren, 2022). Extended reality technologies offer a visualized process to enhance circular productivity (Harichandran et al., 2023). Geographic Information System enhances the identification, mapping, tracking and management of the materials and wastes in construction projects (Talla & McIlwaine, 2024). The Internet of Things facilitates waste tracking, enhances productivity rates and monitors reusable materials (Mallawaarachchi & Jayakodi, 2023). Robotics improve waste separation and material usage in an automated and highly precise way (Elghaish et al., 2022). Radio Frequency Identification (RFID) enables material tagging for the identification of circular materials (Copeland & Bilec, 2020). In summary, digital technologies have several implementation areas in circular economy and risks encountered in the circular economy practices can be addressed with digital technologies.

Table 2. Identified digital technologies for the circular economy.

ID #	*Digital Tech.*	*References*																							
		A	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*	*J*	*K*	*L*	*M*	*N*	*O*	*P*	*Q*	*R*	*S*	*T*	*U*	*V*	*W*	*X*
T.1	ADM					*	*			*		*		*		*									*
T.2	AI					*	*		*	*		*	*	*							*	*		*	*
T.3	BD					*			*			*	*					*						*	*
T.4	BC	*				*	*	*		*		*	*	*	*					*		*	*	*	*
T.5	BIM	*	*	*	*	*				*	*	*	*	*			*		*			*	*	*	*
T.6	DP		*			*																	*		*
T.7	DT					*						*	*						*			*			*
T.8	DR									*				*									*		
T.9	XR								*	*		*	*												
T.10	GIS					*																			*
T.11	IoT					*	*		*	*		*	*	*				*						*	*
T.12	ROB					*	*		*	*		*		*											
T.13	RFID	*				*			*					*								*	*		

Note. Reference sources are A: Copeland & Bilec, 2020; B: Kovacic et al., 2020; C: Schmeleva & Bezdelov, 2020; D: Wandiga, 2020; E: Çetin et al., 2021; F: Elghaish et al., 2022; G: Hristova, 2022; H: Maiurova et al., 2022; I: Setaki & Timmeren, 2022; J: Behún & Behúnová, 2023; K: Chi et al., 2023; L: Harichandran et al., 2023; M: Jayakodi et al., 2023; N: Jayarathna et al., 2023; O: Khan et al., 2023; P: Kuzminykh et al., 2023; Q: Mallawaarachchi & Jayakodi, 2023; R: Meng et al., 2023; S: Movaffaghi & Yitmen, 2023; T: Oluleye et al., 2023; U: Banihashemi et al., 2024; V: Eze et al., 2024; W: Rodrigo et al., 2024 X: Talla & McIlwaine, 2024. Abbreviations for digital technologies are ADM: Additive Manufacturing, AI: Artificial Intelligence, BD: Big Data, BC: Blockchain, BIM: Building Information Modelling, DP: Digital Platforms, DT: Digital Twins, DR: Drones, XR: Extended Reality, GIS: Geographic Information System, IoT: Internet of Things, ROB: Robotics, RFID: Radio Frequency Identification.

In light of these, this study presented an interaction matrix between circular economy risks and digital technologies. In the interaction matrix, digital technologies are positioned along the horizontal axis and circular economy risks along the vertical axis. By considering the potential contributions of digital technologies to circular economy practices, potential interactions between circular economy risks and digital technologies are identified. The interaction matrix presented in Table 3 aims to illustrate which digital technologies can be utilized to mitigate circular economy risks.

Digital technologies have the potential to address circular economy risks in construction projects. For instance, risks due to improper information management and decision-making can be mitigated by the integration of AI, big data, blockchain, BIM, digital platforms, digital twins, and extended reality. In addition, design and construction-related risks like standardization, improper circular design and time-consuming processes can be minimized by implementing additive manufacturing, BIM, digital twins and extended reality. Circular material risks in terms of transparency, inventory, tracking and availability can be managed by AI, big data, BIM, digital twins, drones, blockchain, GIS and RFID. As recycling, reuse and regeneration play an important scope in the circularity of construction projects, materials recovery and waste management risks can be handled with the integration of AI, big data, BIM, digital twins, drones, extended reality, IoT, robotics and RFID.

Table 3. Interaction matrix for circular economy risks and digital technologies.

Circular Economy Risks	*Digital Technologies*												
	T.1	T.2	T.3	T.4	T.5	T.6	T.7	T.8	T.9	T.10	T.11	T.12	T.13
R.1		*											*
R.2		*	*			*			*				*
R.3	*	*						*	*		*	*	*
R.4		*	*	*	*	*	*		*				*
R.5		*	*	*	*		*	*		*		*	*
R.6				*									
R.7		*	*										
R.8				*								*	
R.9	*				*				*				
R.10	*				*		*		*				
R.11		*					*	*			*	*	*
R.12		*	*										*
R.13			*							*			*
R.14					*		*				*		
R.15		*										*	
R.16									*			*	
R.17				*	*		*	*		*	*		*
R.18		*											
R.19		*	*										
R.20						*		*					

Conclusion

This study presented an interaction matrix to identify which digital technologies can be beneficial for managing circular economy risks. The literature mentioned circular economy risks across management, economic, technical, materials, technology, and logistics aspects. A total of 13 digital technologies were identified, with artificial intelligence, RFID, big data, BIM, digital twins, extended reality, and robotics emerging as the leading digital technologies for circular economy risk management based on the frequencies provided in the interaction matrix (Table 3).

In addition, this study reveals the gap in the current literature by providing insights into interactions between circular economy risks and digital technologies. The interaction matrix aims to serve as a preliminary guideline for scholars and practitioners in the application of circular economy risks and digital technologies. Future studies can focus on validating the interactions between digital technologies and circular economy risks. Additionally, the study could be enhanced by incorporating technical and industry reports of the subject matter would provide additional insights for future studies. Finally, the identified technologies can be further explored and combined to assess which ones are most effective for mitigating circular economy risks.

References

AlMashaqbeh, S., & Munive-Hernandez, J. E. (2023). Risk analysis under a circular economy context using a systems thinking approach. *Sustainability*, *15*(5), 4141.

Antikainen, M., Uusitalo, T., & Kivikytö-Reponen, P. (2018). Digitalisation as an enabler of circular economy. *Proceedings of 10th CIRP Conference on Industrial Product-Service Systems*, pp. 45-49.

Banihashemi, S., Meskin, S., Sheikhkhoshkar, M., Mohandes, S. R., Hajirasouli, A., & Lenguyen, K. (2024). Circular economy in construction: the digital transformation perspective. *Cleaner Engineering and Technology*, 100715.

Behún, M., & Behúnová, A. (2023). Advanced innovation technology of BIM in a circular economy. *Applied Sciences*, *13*(13), 7989.

Chan, A. P. C., & Chan, A. P. L. (2004). Key performance indicators for measuring construction success. *Benchmarking: An International Journal*, *11*(2), 203-221.

Chauhan, C., Parida, V., & Dhir, A. (2022). Linking circular economy and digitalisation technologies: a systematic literature review of past achievements and future promises. *Technological Forecasting and Social Change*, *177*, 121508.

Chi, Z., Liu, Z., Wang, F., & Osmani, M. (2023). Driving circular economy through digital technologies: current research status and future directions. *Sustainability*, *15*(24), 16608.

Cook, E., Velis, C. A., & Black, L. (2022). Construction and demolition waste management: a systematic scoping review of risks to occupational and public health. *Frontiers in Sustainability*, *3*, 924926.

Copeland, S., & Bilec, M. (2020). Buildings as material banks using RFID and building information modeling in a circular economy. *Procedia Cirp*, *90*, 143-147.

Cuvelier, A. A., Hery, M., & Malenfer, M. (2022). From globalization to circular economy, which issues for health and safety at work? *Proceedings of the 21st Congress of the International Ergonomics Association*, pp. 592-596.

Çimen, Ö. (2021). Construction and built environment in circular economy: a comprehensive literature review. *Journal of Cleaner Production*, *305*, 127180.

Çetin, S., De Wolf, C., & Bocken, N. (2021). Circular digital built environment: an emerging framework. *Sustainability*, *13*(11), 6348.

Dulia, E. F., Ali, S. M., Garshasbi, M., & Kabir, G. (2021). Admitting risks towards circular economy practices and strategies: An empirical test from supply chain perspective. *Journal of Cleaner Production*, *317*, 128420.

Elghaish, F., Matarneh, S. T., Edwards, D. J., Rahimian, F. P., El-Gohary, H., & Ejohwomu, O. (2022). Applications of Industry 4.0 digital technologies towards a construction circular economy: gap analysis and conceptual framework. *Construction Innovation*, *22*(3), 647-670.

Eze, E. C., Sofolahan, O., Ugulu, R. A., & Ameyaw, E. E. (2024). Bolstering circular economy in construction through digitalisation. *Construction Innovation*.

Figueirôa, Í., do Carmo Duarte Freitas, M., Tavares, S. F., & Bragança, L. (2023). How circular economy strategies can be implemented in the dwelling renovation design phase. In *Creating a roadmap towards circularity in the built environment* (pp. 47-56). Springer Nature.

Geissdoerfer, M., Savaget, P., Bocken, N. M., & Hultink, E. J. (2017). The circular economy–a new sustainability paradigm? *Journal of Cleaner Production*, *143*, 757-768.

Guerra, B. C., Shahi, S., Mollaei, A., Skaf, N., Weber, O., Leite, F., & Haas, C. (2021). Circular economy applications in the construction industry: a global scan of trends and opportunities. *Journal of Cleaner Production*, *324*, 129125.

Harichandran, A., Wandahl, S., & Andersen, L. V. (2023). State of the art technologies that facilitate transition of built environment into circular economy. *Proceedings of the International Symposium on Automation and Robotics in Construction*, pp. 730-737.

Hassan, M. S., Ali, Y., Petrillo, A., & De Felice, F. (2023). Risk assessment of circular economy practices in construction industry of Pakistan. *Science of The Total Environment*, *868*, 161418.

Hristova, T. (2022). The place of the blockchain in the recycling of raw materials. *Proceedings of 8th International Conference on Energy Efficiency and Agricultural Engineering*, pp. 1-4.

Jahan, I., Zhang, G., Bhuiyan, M., & Navaratnam, S. (2022). Circular economy of construction and demolition wood waste—a theoretical framework approach. *Sustainability*, *14*(17), 10478.

Jayakodi, S., Senaratne, S., Perera, S., & Bamdad, K. (2023). Digital technology enabled circularity in the construction industry: a bibliometric study. *Proceedings of the 11th World Construction Symposium*, pp. 460-470.

Jayarathna, H. S. N. M., Perera, B. A. K. S., Atapattu, A. M. D. S., & Rodrigo, M. N. N. (2023). Synergy between blockchain and circular economy in improving construction waste management: a literature review. *Proceedings of the 11th World Construction Symposium*, pp. 1024-1038.

Kazancoglu, Y., Ozkan-Ozen, Y. D., Sagnak, M., Kazancoglu, I., & Dora, M. (2023). Framework for a sustainable supply chain to overcome risks in transition to a circular economy through Industry 4.0. *Production Planning & Control*, *34*(10), 902-917.

Khan, S. A., Jassim, M., Ilcan, H., Sahin, O., Bayer, İ. R., Sahmaran, M., & Koc, M. (2023). 3D printing of circular materials: comparative environmental analysis of materials and construction techniques. *Case Studies in Construction Materials*, *18*, e02059.

Kovacic, I., Honic, M., & Sreckovic, M. (2020). Digital platform for circular economy in AEC industry. *Engineering Project Organization Journal*, *9*(1).

Kuzminykh, A., Parente, M., Vieira, V., Granja, J., & Azenha, M. (2023). RecycleBIM approach towards integrated data management for circularity: proof of concept in a RC building. *Proceedings of International RILEM Conference on Synergising Expertise Towards Sustainability and Robustness of CBMs and Concrete Structures*, pp. 252-262.

Lima, L., Trindade, E., Alencar, L., Alencar, M., & Silva, L. (2021). Sustainability in the construction industry: a systematic review of the literature. *Journal of Cleaner Production*, *289*, 125730.

Maiurova, A., Kurniawan, T. A., Kustikova, M., Bykovskaia, E., Othman, M. H. D., Singh, D., & Goh, H. H. (2022). Promoting digital transformation in waste collection service and waste recycling in Moscow (Russia): applying a circular economy paradigm to mitigate climate change impacts on the environment. *Journal of Cleaner Production*, *354*, 131604.

Mallawaarachchi, B. H., & Jayakodi, S. (2023). Internet of things (IoT)-enabled industrial symbiosis model for construction material sharing: bibliometric analysis. *Proceedings of the 11th World Construction Symposium*, pp. 565-605.

Meng, X., Das, S., & Meng, J. (2023). Integration of digital twin and circular economy in the construction industry. *Sustainability*, *15*(17), 13186.

Movaffaghi, H., & Yitmen, I. (2023). Framework for dynamic circular economy in the building industry: integration of blockchain technology and multi-criteria decision-making approach. *Sustainability*, *15*(22), 15914.

Norouzi, M., Chàfer, M., Cabeza, L. F., Jiménez, L., & Boer, D. (2021). Circular economy in the building and construction sector: a scientific evolution analysis. *Journal of Building Engineering*, *44*, 102704.

Oluleye, B. I., Chan, D. W., & Antwi-Afari, P. (2023). Adopting artificial intelligence for enhancing the implementation of systemic circularity in the construction industry: a critical review. *Sustainable Production and Consumption*, *35*, 509-524.

Parusheva, S. (2019). Digitalization and digital transformation in construction-benefits and challenges. *Proceedings of the International Conference Dedicated to the 50th anniversary of the Department of Informatics*, pp. 126-134.

Phelan, A., & Dawes, L. (2013). Megaprojects, affected communities and sustainability decision making. *Proceedings of Sustainable Engineering Society Conference: Looking Back, Looking Forward*, pp. 42-51.

Rodrigo, N., Omrany, H., Chang, R., & Zuo, J. (2024). Leveraging digital technologies for circular economy in construction industry: a way forward. *Smart and Sustainable Built Environment*, *13*(1), 85-116.

Rostami, A., & Oduoza, C. F. (2017). Key risks in construction projects in Italy: contractors' perspective. *Engineering, Construction and Architectural Management, 24*(3), 451-462.

Sariatli, F. (2017). Linear economy versus circular economy: a comparative and analyzer study for optimization of economy for sustainability. *Visegrad Journal on Bioeconomy and Sustainable Development*, *6*(1), 31-34.

Schmeleva, A., & Bezdelov, S. (2020). Environmental aspects of the housing renovation program in Moscow under sharing and circular economy conditions. *Proceedings of E3S Web of Conferences*, p. 05013.

Setaki, F., & Timmeren, A. V. (2022). Disruptive technologies for a circular building industry. *Building and Environment*, *223*, 109394.

Silva, G. A., Warnakulasooriya, B. N. F., & Arachchige, B. (2015). Critical success factors for construction projects: a literature review. *Proceedings of 12th International Conference on Business Management*.

Statsenko, L., Samaraweera, A., Bakhshi, J., & Chileshe, N. (2023). Construction 4.0 technologies and applications: a systematic literature review of trends and potential areas for development. *Construction Innovation*, *23*(5), 961-993.

Talla, A., & McIlwaine, S. (2024). Industry 4.0 and the circular economy: using design-stage digital technology to reduce construction waste. *Smart and Sustainable Built Environment*, *13*(1), 179-198.

Tariq, J., & Gardezi, S. S. S. (2023). Study the delays and conflicts for construction projects and their mutual relationship: a review. *Ain Shams Engineering Journal*, *14*, 101815.

Tung, Y. H., Chia, F. C., & Yong, F. Y. Y. (2021). Exploring the usage of digital technologies for construction project management. *Planning Malaysia*, *19*, 13-22.

Tuni, A., Ijomah, W. L., Gutteridge, F., Mirpourian, M., Pfeifer, S., & Copani, G. (2023). Risk assessment for circular business models: a fuzzy Delphi study application for composite materials. *Journal of Cleaner Production*, *389*, 135722.

Wandiga, C. A. (2020). Methodological review: socio-cultural analysis criteria for BIM modeling and material passport tracking of agriwaste as a building construction raw material. *MRS Energy & Sustainability*, *7*, E25.

Wu, P. Y., Mjörnell, K., Mangold, M., Sandels, C., & Johansson, T. (2021). A data-driven approach to assess the risk of encountering hazardous materials in the building stock based on environmental inventories. *Sustainability*, *13*(14), 7836.

Wuni, I. Y., & Abankwa, D. A. (2023). Understanding the key risks in circular construction projects: from systematic review to conceptual framework. *Construction Innovation*.

The Effect of Artificial Neural Networks on Cost Estimation in Construction Projects: A Literature Review

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Abstract

Since cost estimation in construction projects is one of the most critical factors for the project's success, it is impossible to avoid losses that may occur if the cost estimation is not done correctly or if the cost is not managed well throughout the process. Although artificial intelligence technologies have been used in many sectors for a long time in project management and cost estimation, current technologies have only recently started to increase, as the construction industry is a sector that can hardly adapt to innovations. Many of these artificial intelligence technologies are used in the construction industry. Artificial Neural Networks (ANNs), which can provide very successful results, especially in prediction, are used for many different purposes, from compressive strength against loads to predicting building damage levels after earthquakes. However, the most common use is to predict the cost of construction projects. ANNs, which can produce results with very high prediction accuracy in light of the data taught to the model by considering variable parameters, will enable accurate cost estimation in every process of many projects and will shed light on future projects and create accurate data for new calculations. Accordingly, this paper aims to investigate the literature on ANN's use and effect on cost estimation in construction projects.

Keywords: *artificial neural networks, construction project, cost estimation, literature review.*

Introduction

The construction industry in developing nations is plagued by a range of productivity challenges. These challenges encompass a shortage of skilled workers, low productivity levels, significant material wastage, and frequent cost and schedule overruns (Pradhananga et al., 2021). The additional costs and time required to fulfil obligations specified in relevant contracts directly impact the potential profit derived from construction projects. Project owners will suffer financial losses if they cannot begin using the completed project by the planned completion date.

Moreover, the contractor will face additional expenses due to the prolonged duration of the work (Chapman, 2001; Akinosho et al., 2020; Musarat et al., 2021; Fobiri et al., 2022). Therefore, public and private construction endeavors are vital in advancing all facets of life and should be executed within a predetermined time and budgetary parameters. However, this ideal scenario does not always materialize; projects may encounter delays, leading to extended timelines and potentially surpassing the initially budgeted costs. A project succeeds when it meets technical specifications, adheres to the timetable, and remains within the financial constraints. The contractor and the client must establish reliable estimates to ensure project completion. These estimates enable the client to determine whether to continue construction while providing the contractor with essential resources to perform a cost-benefit analysis (Hammad et al., 2014; Gunduz et al., 2015; Ghosh et al., 2017; Ghazal & Hammad, 2020). In the context of construction projects, exceeding time and cost budgets is a common occurrence and can lead to severe consequences. Cost overrun predictions traditionally rely on expert opinions or the review of historical data, both of which can be time-consuming, subjective, and may overlook significant factors. Artificial neural networks have demonstrated encouraging outcomes in forecasting cost overruns using data acquired from construction projects.

Considering that the primary purpose of a project's success is to complete it within the desired cost, time and quality parameters, making high-accurate cost estimates using ANN models will not only reduce costs but also make a healthier contribution to the success goals of the project (Ambrule & Bhirud, 2017).

As the literature proves, time and cost overruns frequently cause problems in construction projects. Artificial neural networks (ANN) have been recognized as a significant tool for improving time and cost management in construction projects by eliminating the limitations of traditional estimation methods. In this regard, this paper aims to investigate the literature ANN's use and effect on cost estimation in construction projects. The study's results will demonstrate the effectiveness of employing artificial neural networks holds significant potential to enhance efficiency in the construction industry by enabling more effective project planning, budget management, and resource allocation.

Methodology

A detailed literature review was conducted to examine the existing studies on artificial neural networks and cost estimation in detail. Scopus was chosen as the database because it has a broader scope and provides access to newer publications (Opoku et al., 2021). Title-Abstract-Keywords filtering in Scopus's advanced search engine was used with three parts. The first part was "artificial neural networks OR ann", while the second part was "cost", and the third part was "construction project OR construction sector". The publications obtained in the search results unrelated to the construction industry were eliminated. Thus, publications published since 2010 were selected to be analyzed within the scope of the study.

ANN Use and Effect on Cost Estimation in Construction Projects

This section presents an analysis of the selected publications in the discipline of the impact of artificial neural networks on construction costs. Forty publications were examined from significant sources hosting specialized scientific publications and providing comprehensive information (ScienceDirect, MDPI, "Multidisciplinary Digital Publishing Institute", ASCE, Taylor&Francis). When examined over time, the trend in published publications reveals a considerable and steady interest in the impact of artificial neural networks on construction costs, with a recent increase. Figure 1 shows the graph that depicts the yearly publication output on artificial neural networks with the cost estimation context from 2010 to 2023. The data suggests a steady publication increase, with some fluctuations over this period. The number of publications appears to increase yearly from 2020 to 2023. There appears to be a significant increase in the between 2022 and 2023.

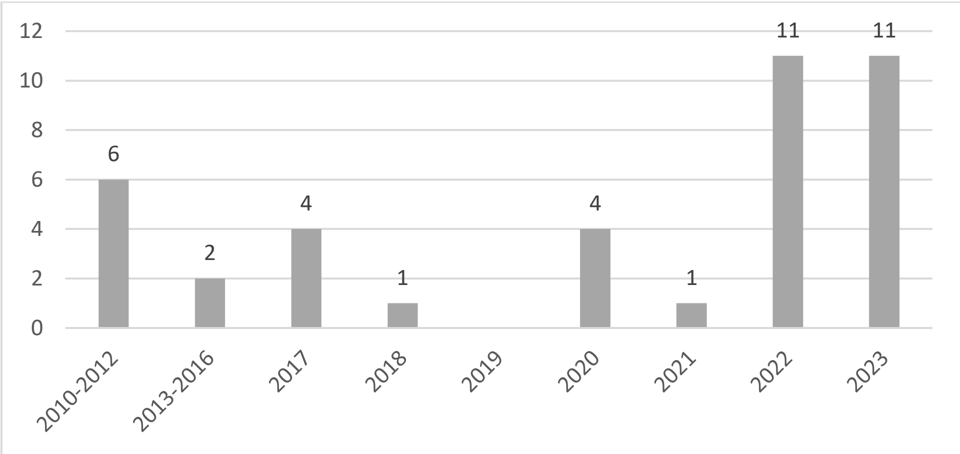

Figure 1: Yearly publication output.

The examined publications contain valuable information from research across various topics. These publications' keywords focus on subjects such as artificial neural networks, machine learning, prediction of time and cost overruns in construction projects, the COVID-19 pandemic, strength prediction, price prediction models, building costs, and construction labor efficiency. In Figure 2, a word cloud is given to represent the frequency of keywords within the selected publications visually. The word cloud reinforces the focus on machine learning techniques, particularly artificial neural networks, in conjunction with cost management. Words like "machine learning," "artificial intelligence," "cost management," and "algorithms" are all prominent. This suggests that a key area of research is applying artificial intelligence algorithms to improve cost estimation and forecasting. Other terms like "safety," "engineering," "construction," and "project" imply a focus on real-world applications of these artificial intelligence techniques in the construction management domain.

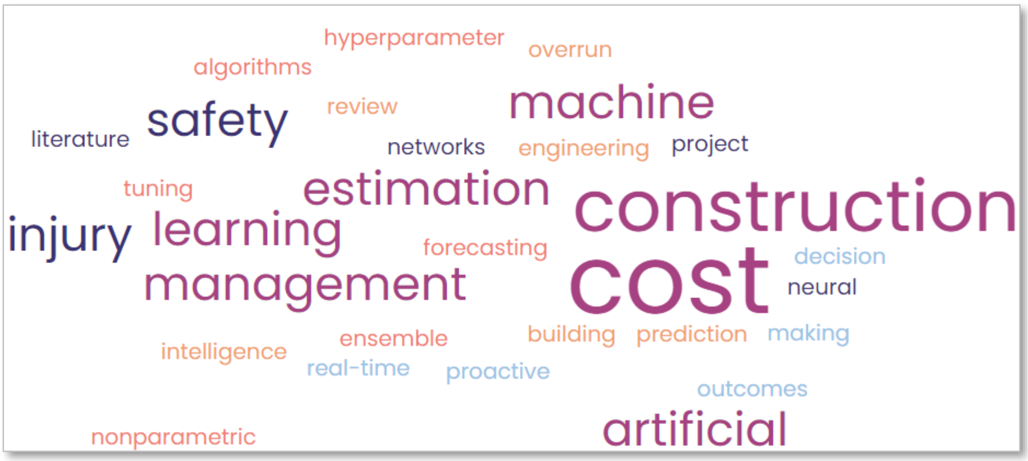

Figure 2: Word cloud of keyword.

The analyzed publications include mobile crane configuration selection, structural assembly analysis, artificial intelligence applications, cost control analysis, and future challenges. The findings provide valuable guidance on how artificial intelligence and machine learning techniques can be used across various applications in the construction industry. These studies contribute significantly to practices that enhance productivity, cost control, and project success rates within the sector. The contents of the publications generally cover the challenges and advantages of using artificial intelligence tools in cost estimation (Juszczyk, 2017), the applicable potentials of artificial intelligence technology in construction management (Eber, 2020), how artificial neural networks can be utilized in pre-design cost estimation (Ambrule & Bhirud, 2017), a case analysis of an artificial neural network-driven method for estimating structural costs in building projects in the Philippines (Roxas & Ongpeng, 2014), a comparison of artificial intelligence and parametric modelling techniques in construction cost estimation and the current situation (Abioye et al., 2021), and the factors influencing the adoption of artificial intelligence technology in the construction industry in South Africa (Tjebane et al., 2022).

Several publications covering the research topic have been reviewed. Among these, "Construction Industry Price Prediction Models" is a systematic literature review (Ma et al., 2023), "Artificial Intelligence in Construction Projects" is a systematic scoping review (Bang & Olsson, 2022), and a study on the application of artificial neural networks (ANN) in macro BIM cost analysis (Juszczyk, 2017). Additionally, publications focusing on cost and budget estimation, which is critical for planning, executing, and completing projects in the construction sector, were included in the review. One such publication discusses the effective use of machine learning methods in cost estimation and optimization processes, highlighting data-driven methods developed to accurately predict and optimize the costs of construction projects (Pham et al., 2023). Another publication, which includes Extreme Gradient Boosting-based machine learning approaches for estimating the cost of green building, evaluates a specific machine learning model developed to predict the costs of sustainable building projects (Alshboul et al., 2022).

The reviewed publications are authored by scholars from different countries, indicating global interest. India and Egypt are at the top of the list, with four publications. Three publications follow this: from Jordan and China, and two are from Iran, Australia, Taiwan, Germany, and Poland. One publication each is from South Korea, Canada, Saudi Arabia, Vietnam, Thailand, Norway, South Africa, the United Kingdom, Finland, the Philippines, Switzerland, and Kenya. This geographical distribution shows that publications received contributions from various regions, but India and Egypt stand out. As for collaborations in research, the authorship analysis showed that different authors worked on the 40 publications, although some were written in the same countries. Greater international collaboration could bring together diverse perspectives, identify differences in practices, provide comparative analysis, and contribute to dissemination in the field.

If we examine the contributions of these publications to cost estimation with artificial neural networks, Artificial neural networks, one of the most advanced subfields of artificial intelligence technology, are frequently used in engineering due to their ability to analyze different parameters and produce highly accurate outputs simultaneously. In construction management, they have been used multiple times to predict construction costs and have shown successful results (Ambrule & Bhirud, 2017). Arabzadeh et al. (2018) formulated artificial neural networks, regression, and hybrid models to estimate the costs of global storage tanks. The findings revealed that hybrid neural networks outperformed both hybrid regression models and individual neural networks. Juszczyk (2017) suggested that artificial neural networks could be applied as a feasible supportive artificial intelligence tool in macro BIM cost analysis based on the findings of his studies. Roxas and Ongpeng (2014) focused on developing a model that uses artificial neural networks to estimate the overhead costs of construction projects in the

Philippines, an island country. Four parameters were determined as input: volume of the concrete area of the formworks, weight of reinforcing steel, number of floors and number of basement floors. The developed artificial neural network model also estimated the entire structural cost of the buildings, which gave satisfactory results after extensive training and testing phases. Alqahtani and Whyte (2013) developed an ANN model to calculate all construction costs using significant cost items. Tatari and Kucukvar (2011) developed an artificial neural network model to estimate project costs for registered green buildings. Cheng et al. (2010) created approximate cost estimates for completion in the construction industry by building a hybrid model using artificial neural networks and fuzzy logic methods. Caputo and Pelagagge (2008) compared the values they found with parametric functions to predict the production costs of large-volume and complex-shaped pressure pipes using artificial neural network methods. Wilmot and Mei (2008) designed an artificial neural network-based model to replicate historical trends in highway construction costs and accurately predict future expenditures. Kim et al. (2005) aimed to estimate the costs of residential buildings by developing a hybrid model based on artificial neural networks and genetic algorithms. Günaydın and Doğan (2004) presented an artificial neural network-based model for construction cost estimation using eight design parameters for the project's design phase. The model they developed achieved a prediction accuracy of 93%.

Conclusion

This study presented a literature review with the aim of examining the existing studies on the use and effect of artificial neural networks on construction cost estimation. The study highlighted the limitations of traditional estimating methods and emphasized the potential of ANN techniques to make more accurate cost overrun predictions by utilizing increasing amounts of data. In this context, the paper demonstrated that ANN could be a significant tool for improving time and cost management in construction projects. The study results showed that using ANN can enhance efficiency in the construction industry by enabling more effective project planning, budget management, and resource allocation.

The study examined the potential of ANN to enhance efficiency in the construction industry, particularly in key areas such as project planning, budget management, and resource allocation. It determined whether this innovative approach aligns with a vision of broader acceptance and systematic use within the construction sector. The examined publications indicated that ANN techniques could be an essential strategy for addressing cost and time overruns in construction projects. The findings of this study suggest that adopting artificial intelligence-based approaches may be valuable for more effectively planning and managing future construction projects.

References

Abioye, S. O., Oyedele, L. O., Akanbi, L., Ajayi, A., Delgado, J. M. D., Bilal, M., Akinade, O. O., & Ahmed, A. (2021). Artificial intelligence in the construction industry: A review of present status, opportunities and future challenges. *Journal of Building Engineering*, *44*, 103299.

Akinosho, T. D., Oyedele, L. O., Bilal, M., Ajayi, A. O., Delgado, M. D., Akinade, O. O., & Ahmed, A. A. (2020). Deep learning in the construction industry: A review of present status and future innovations. *Journal of Building Engineering*, *32*, 101827.

Alqahtani, A. & Whyte, A. (2013). Artificial neural networks incorporating cost significant Items towards enhancing estimation for life-cycle costing of construction projects. *Australasian Journal of Construction Economics and Building,13*(3), 51-64.

Alshboul, O., Shehadeh, A., Almasabha, G., & Almuflih, A. S. (2022). Extreme gradient boosting-based machine learning approach for green building cost prediction. *Sustainability*, 14, 6651. https://doi.org/10.3390/su14116651

Ambrule, V. R., & Bhirud, A. N. (2017). Use of artificial neural network for pre design cost estimation of building projects. *Int. J. Recent Innovation Trends Comput. Commun., 5*(2), 173–176.

Arabzadeh, V., Niaki, S. T. A., & Arabzadeh V. (2018). Construction cost estimation of spherical storage tanks: Artificial neural networks and hybrid regression—GA algorithms. *J. Ind. Eng. Int., 14*(4), 747.

Bang, S., & Olsson N. (2022). Artificial intelligence in construction projects: A systematic scoping review. *Journal of Engineering, Project, and Production Management, 12*(3), 224-238.

Caputo, C. A., & Pelagagge, M. (2008). Parametric and neural methods for cost estimation of process vessels. *International Journal of Production Economics, 112*(2), 932-954.

Chapman, R. J. (2001). The controlling infuences on efective risk identifcation and assessment for construction design management. *International Journal of Project Management, 19*(3), 147–160.

Cheng, M., Tsai, H., & Sudjono, E. (2010). Conceptual cost estimates using evolutionary fuzzy hybrid neural network for projects in construction industry. *Expert Systems with Applications, 37*, 4224–4231.

Eber, W. (2020). Potentials of artificial intelligence in construction management. *Organization, Technology and Management in Construction, 12*, 2053–2063

Fobiri, G., Musonda, I., & Muleya, F. (2022). Reality capture in construction project management: A review of opportunities and challenges. *Buildings, 12*(9), 1381.

Ghazal, M., & Hammad, A. (2020). Application of knowledge discovery in database (KDD) techniques in cost projects. *International Journal of Construction Management, 22*(9), 1632–1646.

Ghosh, M., Kabir, G., & Hasin, M. A. A. (2017). Project time–cost trade-of: A bayesian approach to update project time and cost estimates. *International Journal of Management Science and Engineering Management, 12*(3), 206–215.

Gunaydın, H. M., & Dogan, S. Z. (2004). A neural network approach for early cost estimation of structural systems of buildings. *International Journal of Project Management, 22*(7), 595-602.

Gunduz, M., Nielsen, Y., & Ozdemir, M. (2015). Fuzzy assessment model to estimate the probability of delay in Turkish construction projects. *Journal of Management in Engineering, 31*(4), 04014055.

Hammad, A. A. A., Ali, S. M. A., Sweis, G. J., & Bashir, A. (2008). Prediction model for construction cost and duration in Jordan. *Jordan Journal of Civil Engineering, 2*(3), 250–266.

Juszczyk, M. (2017). Studies on the ANN implementation in the macro BIM cost analyzes. *Przegląd Naukowy Inżynieria i Kształtowanie Środowiska, 26*.

Kim, G. H., Seo, D. S., & Kang, K. I. (2005). Hybrid models of neural networks and genetic algorithms for predicting preliminary cost estimates. *Journal of Computing in Civil Engineering*, *19*(2), 208–211.

Ma, M., Tam, V. W. Y., Le, K. N., & Osei-Kyei, R. (2023). A systematic literature review on price forecasting models in construction industry. *International Journal of Construction Management*, 1–10. https://doi.org/10.1080/15623599.2023.2241761

Musarat, M. A., Alaloul, W. S., & Liew, M. S. (2021). Impact of infaction rate on construction projects budget: A review. *Ain Shams Engineering Journal, 12*(1), 407–414.

Opoku, D. G. J., Perera, S., Osei-Kyei, R., & Rashidi, M. (2021). Digital twin application in the construction industry: A literature review. *Journal of Building Engineering*, *40*.

Pham, T. Q. D., Le-Hong, T., & Tran, X. V. (2023). Efficient estimation and optimization of building costs using machine learning. *International Journal of Construction Management*, *23*(5), 909–921. https://doi.org/10.1080/15623599.2021.1943630

Pradhananga, P., ElZomor, M., & Santi Kasabdji, G. (2021). Identifying the challenges to adopting robotics in the US construction industry. *Journal of Construction Engineering and Management, 147*(5), 05021003.

Roxas, C. L. C., & Ongpeng, J. M. C. (2014). An artificial neural network approach to structural cost estimation of building projects in the Philippines. *DLSU Research Congress*, De La Salle University, Manila 1-7.

Tatari, O., & Küçükvar, M. (2011). Cost premium prediction of certified green buildings: A neural network approach. *Building and Environment, 46*(5), 1081-1086.

Tjebane M. M., Musonda, I., & Okoro, C. (2022). Organisational factors of artificial intelligence adoption in the South African construction industry. *Front. Built Environ., 24 March 2022 Sec. Construction Management, 8*.

Wilmot C. G., & Mei, B. (2008). Neural network modeling of highway construction costs. *Journal of Construction Engineering and Management, 131*(7), 765-771.

Classification of Delay Factors in the Construction Industry According to Stakeholders and Project Types

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Abstract

In the construction industry, project management aims to effectively manage cost, quality, and time. In this context, it is possible to prevent the delay among the problems in the life cycle of construction projects with the effective implementation of time management. In the construction process, it is an important step to identify the factors that cause delay to manage time effectively. These factors may depend on different factors such as the stakeholder groups involved in the construction process and the nature of the project. Being able to determine which factors are affected by the factors that cause the delay will enable the correct and effective solution to be produced and to search for the source of the problem. In this study, the factors that cause delays in construction projects are determined and it is revealed from which stakeholder groups these factors originate. In addition, it is investigated whether the delay factors determined vary according to the nature of the project. Thus, it is aimed to determine the delay factors that should be considered in the construction projects for time management and the delay factors classified according to stakeholder groups and nature of project.

Keywords: *construction management, delay factors, project management, time management.*

Introduction

When it is desired to evaluate the success of a construction project, it is examined that the project is completed within the specified time, planned budget, in accordance with the qualifications specified in the specification (Chin & Hamid, 2015). So, time management, is the whole of the activities carried out to complete a project within the specified time, is one of the most important success factors for the construction projects. In cases where time cannot be managed effectively, problems like delay arise.

Delay refers to a fact or action that occurs after the planned time or later than stipulated in the contract for the stakeholders to terminate a construction project (Kikwasi, 2012). In other words, delay, one of the common problems in the construction projects, means not being completed within the originally planned time. It is seen that time management problems and loss of time causes to delay. In addition to loss of time, it leads to delay such as cost excesses, disputes, deterioration of stakeholder relations, legal processes, and contract termination. Considering the negativities encountered in the delayed projects and the frequency of delays in the construction industry, it is important to identify the factors that cause the delay and take precautions. In this study, the factors that cause delays in construction projects are determined and it is revealed from which stakeholder groups these factors originate.

Delay Factors Caused by Stakeholders

Many different stakeholders are involved in the construction projects. Each stakeholder has different workload and impact during the project lifecycle. Negative actions of stakeholders in the project process cause delays. So, it will be an important step to classify the delay factors according to stakeholder groups to carry out time management effectively and to take precautions against delays.

In the literature, many studies have been carried out on determining the factors that cause delays in the construction projects. In this study, it is aimed to determine the delay factors in the literature that should be considered in the construction projects for time management and the delay factors classified according to stakeholder groups and nature of project. To reach this aim, a literature review was realized, and the review was limited to research on delay factors in the last 10 years (2014 – 2023). With the limitations of "construction" AND "delay" AND "factor", "hospital" AND "project" AND "factor", "schedule" AND "delay" AND "construction" on Scopus, 42 articles were determined on total. It was observed that 29 of the 42 articles were closed relation with the delay factors. In listed 29 articles, a total of 1062 delay factors were obtained. These 1062 delay factors were filtered, and the same ones were combined. As a result of filtration, 90 delay factors were obtained and classified according to the stakeholder who causes them (Table 1).

Table 1. Delay factors caused by stakeholders.

Stake-holders	**Code**	**Delay Factors**	**Source**
Client	F1	Problems arising from the existing building stock in the project area	[8]
Client	F2	Frequent change of people in the project organization	[10], [14], [29]
Client	F3	Inexperienced technical staff	[1], [4], [5], [6], [10], [23], [28]
Client	F4	Complexity of the project and changes in the scope of work	[1], [2], [3], [4], [6], [7], [10], [13], [14], [18], [21], [23], [24], [26], [27], [28]
Client	F5	Late receipt and inspection of completed work	[11], [26], [29]
Client	F6	Termination of contract, change of contractor	[14]
Client	F7	Late delivery of documents to the contractor	[23], [24]

Client	F8	Ineffective late penalties and contractual sanctions	[1], [5], [12], [14]
Client	F9	Unrealistic duration of the contract	[1], [4], [5], [12], [13], [14], [15], [17], [18], [21], [25], [28]
Client	F10	Errors and inconsistencies in the contract	[1], [2], [3], [4], [5], [11], [21], [29]
Client	F11	Selecting the contractor with the lowest bid, assigning work to an inadequate contractor	[1], [4], [11], [12], [21], [23], [24], [25], [28]
Client	F12	Delay in delivering the site to the contractor	[1], [4], [8], [9], [12], [14], [15], [24], [29]
Client	F13	Client's delays in making decisions	[1], [3], [4], [5], [6], [8], [10], [11], [12], [13], [14], [17], [18], [20], [21], [22], [23], [25], [26], [27], [28], [29]
Client	F14	Contract changes by the client during construction	[1], [3], [4], [5], [8], [12], [13], [14], [18], [20], [21], [22], [24], [26], [27], [28], [29]
Client	F15	Delay in progress payments by the client	[1], [2], [4], [5], [6], [8], [9], [11], [12], [13], [14], [15], [17], [18], [19], [20], [21], [22], [24], [25], [26], [27], [28], [29]
Client	F16	Lack of communication and coordination by the client	[1], [2], [3], [4], [5], [8], [9], [10], [12], [14], [15], [17], [18], [20], [21], [22], [25], [26], [27], [28], [29]
Client	F17	Conflicts between clients in common property	[1], [5], [8], [10], [12], [13], [14], [18], [28]
Client	F18	Suspension of work due to client	[1], [8], [12]
Client	F19	Misunderstandings in technical relations with contractors	[8], [9], [14]
Client	F20	Design changes/additional works made by the client	[1], [2], [4], [7], [9], [10], [11], [14], [17], [18], [23], [24], [26]
Client	F21	Incompetence and inexperience of the client	[1], [3], [4], [6], [9], [11], [12], [13], [14]
Client	F22	Delays in obtaining permits from government agencies and processes	[1], [2], [4], [6], [9], [10], [11], [12], [13], [15], [17], [19], [26], [28], [29]
Client	F23	No incentive to contractors for early completion	[1], [12]
Client	F24	Excessive bureaucracy in the client’s administration	[1], [5], [13]
Client	F25	Initiation of work before the design is completed	[14]
Client	F26	Frequent changes in the properties of the material during construction	[1], [6], [8], [9], [15], [18], [21], [27]
Client	F27	Slow process of material selection and approval	[4], [8], [17], [18], [21], [22]

Client	F28	Slowdowns in quality control and testing processes	[1], [5], [6], [11], [12], [15], [17], [18], [21], [23], [24], [26], [28], [29]
Consultant	F29	Shortage of the consultant's experience	[4], [8], [9], [10], [12], [13], [18], [21], [23], [27]
Consultant	F30	Poor contract management by the consultant	[1], [4], [5], [6], [8], [10], [11], [13], [17], [18], [20]
Consultant	F31	Lack of coordination of the consultant with the contractor	[8], [23], [28]
Consultant	F32	Inadequacy of the consultant leadership ability	[8], [12], [28]
Consultant	F33	Conflict of the consultant with the design engineer, specification changes by the consultant during construction	[8], [14], [15],[17], [18], [21], [23], [28]
Consultant	F34	Inadequacy of the construction site information provided to the consultant	[6], [8], [14], [18], [21], [24], [28]
Consultant	F35	Conflict between consultant and contractor	[1], [4], [8]
Consultant	F36	Consultant's rigidity in management and control	[2], [12], [23], [27]
Contractor	F37	Inadequate labour and low worker productivity	[1], [2], [4], [5], [6], [7], [8], [11], [12], [13], [14], [15], [17], [18], [20], [21], [22], [25], [26], [27], [28], [29]
Contractor	F38	Inefficient use of equipment, lack of qualified workers/operators	[4], [5], [6], [8], [11], [14], [16], [18], [21], [26], [28], [29]
Contractor	F39	Delay in the supply of necessary equipment	[1], [8], [13], [21], [22], [25], [26], [27]
Contractor	F40	Failure to perform periodic checks of equipment and equipment failures	[1], [2], [4], [6], [8], [9], [13], [15], [16], [17], [18], [20], [26], [27], [28]
Contractor	F41	Shortage of qualified operators	[6], [8], [15], [16], [18], [21]
Contractor	F42	Inadequacy of areas within the construction site related to equipment	[1], [8], [16], [18], [28]
Contractor	F43	Deficiencies in safety procedures and effective supervision	[8], [16], [28]
Contractor	F44	Poor material management	[1], [5], [8], [15], [18], [28]
Contractor	F45	Time loss due to traffic jam	[8], [21], [26]
Contractor	F46	Ineffective project planning and scheduling of the contractor	[1], [2], [4], [5], [6], [8], [10], [11], [12], [13], [14], [15], [17], [18], [20], [21], [22], [25], [26], [27], [28], [29]
Contractor	F47	Contractor's lack of experience in decision-making	[8], [9], [11], [13], [14], [15], [25], [27], [29]
Contractor	F48	Delay in site mobilization	[4], [8], [21], [24]

Contractor	F49	Slowness of the contractor in documentation and bureaucracy	[1], [4], [8], [14], [26]
Contractor	F50	Poor site management and supervision	[1], [2], [4], [5], [8], [9], [11], [12], [13], [14], [15], [17], [18], [19], [20], [21], [22], [23], [24], [26], [27], [28]
Contractor	F51	Problems with subcontractors, incompetent subcontractor	[5], [8], [12], [13], [14], [15], [18], [19], [27], [28], [29]
Contractor	F52	Rework due to errors during construction	[4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [17], [18], [21], [24], [26]
Contractor	F53	Inappropriate construction methods implemented	[1], [2], [3], [4], [5], [6], [8], [9], [14], [15], [17], [18], [23], [27], [28], [29]
Contractor	F54	Contractor's inexperience or lack of use of new software and methods	[3],[4], [5], [8], [14], [15], [18]
Contractor	F55	Poor management skills of the contractor	[5], [8],[9], [10], [12], [13], [15], [18]
Contractor	F56	Communication problems with stakeholders	[1], [4], [8], [14], [18], [21], [23], [26], [27], [28]
Contractor	F57	Delay/poor performance of subcontractors	[2], [3], [4], [9], [11], [14], [15], [19], [21], [22], [26], [28], [29]
Contractor	F58	Difficulties in financing the project by the contractor	[1], [2], [4], [6], [9], [10], [11], [12], [13], [14], [17], [20], [21], [22], [24], [25], [26], [28], [29]
Contractor	F59	Shortage of contractor’s administrative personnel	[1], [2], [3], [4], [11], [12], [13], [18], [24], [26], [28], [29]
Designer	F60	Slowness in approving drawings and projects by the designer	[1], [4], [5], [6], [8], [11], [12], [13], [14], [17], [18], [21], [22], [23], [26], [28]
Designer	F61	Insufficiency of the designer's authority	[4], [6], [8], [10], [20], [21]
Designer	F62	Errors and missing details in the drawings of the design team	[1], [2], [3], [4], [5], [6], [8], [10], [11], [12], [13], [15], [17], [18], [20], [21], [22], [23], [24], [29]
Designer	F63	Financial factors constraining the design	[8], [25]
Designer	F64	The complexity of the project design faced by the designer	[6], [8], [9], [12], [18], [26]
Designer	F65	Communication barriers faced by the designer	[8], [14], [18], [21], [26]
Designer	F66	Shortage of design team experience	[1], [4], [6], [9], [13],[14], [17], [18], [23]
Designer	F67	Mistakes made in design and lack of supervision	[4], [6], [9], [20], [21], [22], [23], [25], [26],[27], [28], [29]

Designer	F68	Failure to identify needs, insufficient information collection	[2], [3], [8], [9], [10], [14], [15], [21], [23]
External	F69	Unexpected weather conditions	[2], [3], [4], [5], [6], [8], [9], [10], [11], [12], [13], [15], [16], [19], [20], [21], [25], [26], [29]
External	F70	Incorrect cost calculations	[2], [3], [5], [8], [10], [13], [21], [28]
External	F71	Restriction due to construction site location and environmental factors	[5], [8], [15], [21], [24], [26], [28]
External	F72	Government regulations	[1], [3], [4], [5], [8], [9], [12], [20], [21], 26], [29]
External	F73	Industry, market, and economic conditions in the country	[2], [4], [5], [10], [12], [15], [19], [20], [24], [25]
External	F74	Force major (War etc.)	[1], [2], [4], [5], [12], [13], [15], [17], [20], [21], [22], [24], 25]
External	F75	Corruption	[12], [21], [25]
External	F76	Workers strikes	[2], [8], [15], [18], [20], [26]
External	F77	Changes in construction site conditions	[1], [8], [14], [17]
External	F78	Unexpected soil conditions	[1], [2], [3], [4], [5], [8], [10], [11], [12], [13], [14], [20], [21], [22], [25], [26], [29]
External	F79	Changes in construction site topography after design	[8]
External	F80	Restricted access to the construction site	[1], [2], [8], [15], [21], [28]
External	F81	Work accidents that occur during construction at the construction site	[2], [6], [8], [9], [12], [14], [15], [19], [20], [21], [26], [28], [29]
Suppliers	F82	Lack of modern equipment	[5], [6], [8], [9], [12], [14], [16], [17], [18]
Suppliers	F83	Equipment with long lead times	[8], [9], [12], [16], [20], [21]
Suppliers	F84	Shortage of materials, production, and supply	[1], [2], [4], [8], [12], [13], [15], [17], [18], [20], [21], [25], [26], [27], [28]
Suppliers	F85	Changes in material quality and problems	[1], [4], [5], [8], [11], [12], [14], [15], [17], [21], [24], [27]
Suppliers	F86	Damage to materials during storage	[1], [8], [15], [17], [29]
Suppliers	F87	Rising material prices	[1], [2], [4], [8], [9], [11], [12], [13], [18], [20], [21], [28], [29]
Suppliers	F88	Material resources that are not available in the domestic market	[1], [6], [8], [21]
Suppliers	F89	Incorrect determination of material deadlines	[1], [14], [15], [17], [18], [20], [21], [28]
Suppliers	F90	Late delivery of material	[1], [4], [5], [6], [8], [20], [21], [22], [25], [26], [27], [28], [29]

Note(s) of Table 1: [1] Shehu et al. (2014); [2]Choundry et al. (2014); [3] Wesnah et al. (2014); [4] Bekr, G.A. (2015); [5] Ruqaishi and Bashir (2015); [6] Hwang et al. (2015); [7] Birgonul et al. (2015); [8] Khair et al. (2016);

[9] Kim et al (2016); [10] Larsen et al. (2016); [11] Bagaya and Song (2016); [12] Alfakhri et al. (2017); [13] Kog (2018); [14] Rachid et al. (2018); [15] Bajjou and Chafi (2018); [16] Indhu et al. (2019); [17] Gopang et al. (2020); [18] Muneeswaran et al. (2020); [19] Hamouda (2020); [20] Egwim et al. (2021); [21] Yap et al. (2021); [22] Ellhusseiny et al. (2021); [23] Sodangi and Salman (2022); [24] Ogbeıfun and Preitorius (2022); [25] Azeez and Radmehr (2022); [26] Tahmasebina and Song (2022); [27] Ajayi and Chinda (2022); [28] Alshibani et al. (2022); [29] Nguyen et al. (2023).

In Table 1, when the delay factors, which are classified according to stakeholder groups, are examined, it is seen that the factors originating from the client (28 factors) caused the delay the most. Also, it is determined that the factors originating from the consultant (6 factors) are the least common. Among the 90 factors listed, the most common factor in the scanned articles (in 22 total research) is the client-related "delay in progress payments by the client" factor numbered with F15. Client-related factors which are F01, F06, F25, are the least common factors (only in 1 research). While examining the relationship between delay factors and stakeholder groups in the scanned articles, it is determined that there are delay factor differences in the types of projects such as superstructure and infrastructure, too. Furthermore, it is observed that some factors can be considered as common factors against the differences in project types.

Delay Factors According to the Project Types

Each construction project is different and unique. However, it is possible to make a main classification in terms of basics qualities of the projects. In this classification, residences, hospitals, schools, and similar structures are classified in the superstructure type whereas roads, bridges and similar transportation structures and structures belonging to energy systems are grouped as infrastructure.

In this step of this study, the delay factors were determined according to the project types. As a result, it was observed that not all the delay factors in the 29 scanned articles belonged to the same project type. 29 articles were divided according to project types. 8 of the articles ([2], [5], [8], [12], [16], [17], [28], and [29]) examined worked on infrastructure projects. In the remaining 21 articles, studies were carried out on superstructures and general construction projects. Although the project types are different, it is seen that some delay factors are repeated in common for both type of project type. In Table 2, it is shown that the common delay factors despite the differences in project types with the percentage of the delay factor in the relevant project type. Also, in Table 2, these delay factors with an incidence rate of more than 50% are listed. The percentage of occurrence is calculated by the ratio of the number of articles in which the relevant factor is detected in the relevant project type to the total number of articles in the relevant project type.

Table 2. Common delay factors according to the project types.

Stakeholders	**Code**	**Delay Factors**	**Infrastructure**	**Superstructure**
Client	F13	Client's delays in making decisions	75,00%	76,19%
Client	F15	Delay in progress payments by the client	87,50%	80,95%
Client	F16	Lack of communication and coordination by the client	87,50%	66,67%

Contractor	F37	Inadequate labour and low worker productivity	87,50%	71,43%
Contractor	F46	Ineffective project planning and scheduling of the contractor	87,50%	71,43%
Contractor	F50	Poor site management and supervision	75,00%	76,19%
External	F69	Unexpected weather conditions	75,00%	61,90%
External	F78	Unexpected soil conditions	62,50%	57,14%

When Table 2 is examined, it is determined that the client related F15 factor is the most common delay factor in both project types. Delay in progress payments by the client, was 87.50% in infrastructure projects and 80.95% in superstructure projects. When the common delay factors determined in infrastructure and superstructure projects are listed, it is determined that factors arising from client (3 Factors), contractors (3 Factors) and external reasons (2 Factors) are frequently seen.

Conclusion

Delay is most common problem in the construction projects and its effect is seen as more than a loss of time. As a result of the study carried out to be useful in solving this problem, The classification of the common delay factors determined in construction projects according to stakeholders was carried out. According to this classification, six groups were formed: client-related (28 factors), consultant-related (6 factors), contractor-related (23 factors), designer-related (9 factors), suppliers (9 factors) and external elements (13 factors). After this classification, it was determined that the factors causing the delay were mainly related to the client. The most common factor among client-related factors is delay in progress payments by the client. The projects where delays should be minimized, it is recommended to conduct studies aimed at reducing client-related factors. The delay factors of progress payments, minimizing the progress payment procedure processes and balancing financing at the beginning of the work may be a step towards a solution.

When the common delay factors of different project types were determined, it was seen that client-related factors come to the fore. When the most common delay factors were listed, it was observed that 3 of the 8 factors are caused by the client. The most common delay factor in both infrastructure and superstructure projects is the delay in progress payments by the client. Similarly, it was determined that contractor-related delay factors constitute 3 out of 8 factors. Ineffective project planning and scheduling of the contractor and inadequate labour and low worker productivity, they were the most common contractor-related delay factors. Prioritizing measures for delay factors that affect each project, regardless of the type of project, will contribute to preventing and reducing delays.

As a result of the study, it is seen that client-related delay factors come to the fore in both classifications. Particularly, it is determined that the delays in payments to the client are evident both in the factors listed among the stakeholders and in the list of common factors created according to the project types. By developing this study, it may be useful to carry out studies on suggestions to reduce the effects of the factors put forward.

References

Alfakhri, A. Y. Y., Ismail, A., Khoiry, M. A., Arhad, I., & Irtema, H. I. M. (2017). A conceptual model of delay factors affecting road construction projects in Libya. *Journal of Engineering Science and Technology, 12*(12), 3286-3298.

Alshibani, A., Julaih, M., Adress, A. Alshamrani, O., & Almaziad, F. (2022). Identifying and ranking the root causes of schedule delays in oil and gas pipeline construction projects. *Energies, 16*(1), 283.

Ajayi, B. O., & Chinda, T. (2022). Impact of construction delay-controlling parameters on project schedule: DEMATEL-system dynamics modeling approach. *Frontiers in Built Environment*, *8*, 799314.

Azeez, L. I., & Radmehr, M. (2022). The investigation of the role of RFID in mitigating delay factors in construction projects. *Technical Gazette*, *29*(3), 933-942.

Bagaya, O., & Song, J. (2016). Empirical study of factors influencing schedule delays of public construction projects in Burkina Faso. *Journal of Management in Engineering, 32*(5), 05016014.

Bajjou, M. S., & Chafi, A. (2018). Empirical study of schedule delay in Moroccan construction projects. *International Journal of Construction Management*, *20*(7), 783-800.

Bekr, G. A. (2015). Causes of delay in public construction projects in Iraq. *Jordan Journal of Civil Engineering, 9*(2), 149-162.

Birgonul, M. T., Dikmen, I., & Bektas, S. (2015). Integrated approach to overcome shortcomings in current delay analysis practices. *Journal of Construction Engineering and Management*, *141*(4), 04014088.

Chin, L. S., & Hamid, A. R. A. (2015). The practice of time management on construction project. *Procedia Engineering, 125*, 32-39.

Choundhry, R. M., Aslam, M. A., & Arain, F. M. (2014). Cost and schedule risk analysis of bridge construction in Pakistan: establishing risk guidelines. *Journal of Construction Engineering and Management, 140*(7), 04014020.

Egwim, C. N., Alaka, H., Toriola-Coker, L. O., Ajayi, S., & Oseghale, R. (2021). Extraction of underlying factors causing construction projects delay in Nigeria. journal of engineering, design and technology, *21*(5), 1323-1342.

Ellhusseiny, H. O., Nosair, I., & Ezeldin, A. S. (2021). Systematic processing framework for analyzing the factors of construction projects' delays in Egypt. *Ain Shams Engineering Journal, 12*, 1501-1511.

Gopang, R. K. M., Imran, Q. B. A., & Nagapan, S. (2020). Assessment of delay factors in Saudi Arabia railway/metro construction projects. *International Journal of Sustainable Construction Engineering and Technology, 11*(2), 225-233.

Hamouda, A. A. H. (2020). External factors of delay that affect the performance of international construction contractors in Kuwait. *International Journal of Integrated Engineering, 12*(8), 8-19.

Hwang, B. G., Zhao, X., & Tan, L. L. G. (2015). Green building projects: schedule performance, influential factors, and solutions. *Engineering, Construction and Architectural Management, 22*(3), 327-346.

Indhu, B., Yogeswari, K., & Dhivya, D. (2019). Ranking of delay factors in road construction project due to improper construction equipment management. *International Journal of Recent Technology and Engineering, 8*(3), 1962-1971.

Kikwasi, G. (2012). Causes and effects of delays and disruptions in construction projects in Tanzania. *Australasian Journal of Construction Economics and Bulding, 1*(2).

Kim, S. Y., Tuan, K. N., & Luu, V. T. (2016). Delay factor analysis for hospital projects in Vietnam. *KSCE Journal of Civil Engineering, 20*(2), 519-529.

Khair, K., Farouk, H., Mohamed, Z., & Mohammad, R. (2016). Causes and effects of delay factors in road construction projects in Sudan. *International Journal of Applied Engineering Research, 11*(18), 9526-9533.

Kog, Y. C. (2018). Project management and delay factors of public housing construction. *Practice Periodical on Structural Design and Construction, 23*(1), 04017028.

Larsen, J. K., Shen, G. Q., Lindhard, S. M., & Brunce, T. D. (2016). Factors affecting schedule delay, cost overrun, and quality level in public construction projects. *Journal of Management in Engineering, 32*(1), 04015032.

Muneeswaran, G., Manoharan, P., Awoyera, P. O., & Adesina, A. (2020). A statistical approach to assess the schedule delays and risks in Indian construction industry. *International Journal of Construction Management, 20*(5), 450-461.

Nguyen, V. S., Nguyen, H. H., Nguyen, D. A., & Hai, D. T. (2023). Delay factors in the construction of irrigation and hydropower projects in Vietnam. *Warsaw University of Technology, Archives of Civil Engineering, 69*(1), 5-20.

Ogbeifun, E., & Pretorius, J. C. (2022). Investigation of factors responsible for delays in the execution of adequately funded construction projects. *Engineering Management in Production and Services, 14*(1), 93-102.

Rachid, Z., Toufik, B., & Mohammed, B. (2018). Causes of schedule delays in construction projects in Algeria. *International Journal of Construction Management, 19*(5), 371-381.

Ruqaishi, M., & Bashir, H. A. (2015). Causes of delay in construction projects in the oil and gas industry in the Gulf Cooperation Council countries: a case study. *Journal of Management in Engineering*, *31*(3), 05014017.

Shehu, Z., Endut, I. R., & Akıntoye, A. (2014). Factors contributing to project time and hence cost overrun in the Malaysian construction industry. *Journal of Financial Management of Property and Construction, 19*(1), 55-75.

Sodangi, M., & Salman, A. (2022). AHP-DEMATEL modelling of consultant related delay factors affecting sustainable housing construction in Saudi Arabia. *International Journal of Construction Management*, *23*(16), 2859-2868.

Tahmasebina, F., & Song, V. (2022). Significant factors causing delay in the Cambodian construction industry. *Sustainability, 14*(6), 3521.

Yap, J. B. H., Goay, P. L., Woon, Y. B., & Skitmore, M. (2021). Revisiting critical delay factors for construction: analysing projects in Malaysia. *Alexandria Engineering Journal, 60,* 1717-1729.

Wesnah, N., El-Ghandour, W., Falls, L. C., & Jergeas, G. (2014). Enhancing project performance by developing multiple regression analysis and risk analysis models for interface. *Canadian Journal of Civil Engineering, 41,* 929-944.

Critical Success Factors for Public-Private Partnership (PPP) Projects: A Bibliometric Analysis

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Abstract

A Public-Private Partnership (PPP) denotes a long-term collaboration between the public and private sectors aimed at financing, designing, building, and operating infrastructure projects or delivering services traditionally provided by the government. PPP has gained increasing attention as a strategic instrument for delivering public infrastructure projects and services. Various types of PPP models have been utilized globally for infrastructure development, exhibiting varying degrees of success and encountering challenges. While PPPs have tremendous potential for infrastructure development, their success depends on managing a complex array of factors. This study aims to conduct a bibliometric analysis of studies on critical success factors for PPP projects. By comprehending these key success factors, stakeholders involved in PPPs can make more informed decisions, thereby enhancing the planning, implementation, and management of PPP projects and, consequently, optimizing outcomes. Future studies in this area hold the potential to inform policy recommendations for governmental bodies and regulatory entities. These recommendations may involve suggesting improvements to existing frameworks, addressing potential barriers, and fostering an environment conducive to successful PPP initiatives. As a result, this study may contribute to overall understanding of PPPs and lay the groundwork for future research efforts in this domain.

Keywords: *bibliometric analysis, critical success factors, public-private partnerships (PPPs).*

Introduction

Public-private partnership (PPP) models are commonly employed to implement a variety of infrastructure projects around the world. The PPP model enhances the economic value of infrastructure outputs while also facilitating overall infrastructure development, including public transportation systems, airports, power plants, and more. The number of PPP projects has steadily increased in developed countries, and developing countries have also embraced PPPs to build and operate their own infrastructure (Wang et al., 2018). Several PPP models have been applied globally in infrastructure construction, each encountering differing levels of success and challenges. Despite their potential for infrastructure development, PPPs require careful management of complex elements for success. A favourable investment environment, economic viability, reliable concessionaire consortium with strong technical strength, sound financial package, and appropriate risk allocation through reliable contractual arrangements are essential (Mulyani, 2021). Identifying and managing critical success factors is crucial for the successful execution of PPP projects. Therefore, this study conducts a bibliometric analysis of studies focusing on critical success factors for PPP projects to enhance understanding and contribute to the future research in this area.

Methodology

The methodology comprises a five-step rigorous procedure commonly followed in bibliometric analyses. The flowchart outlining this review process is presented in Figure 1.

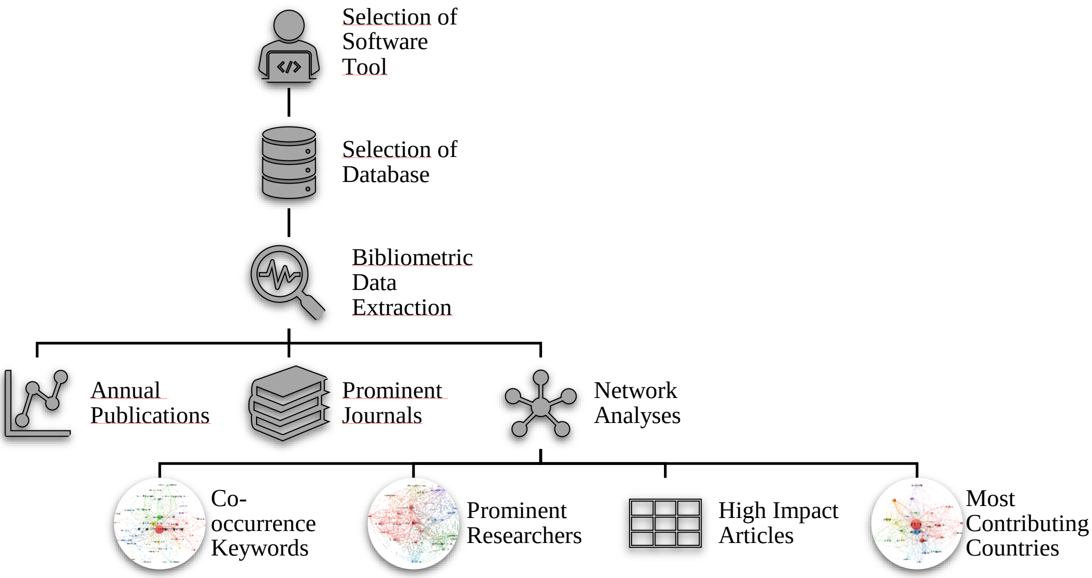

Figure 1: Flowchart of the research methodology.

The first step of bibliometric analysis involved selecting a suitable scientific software tool. Each software tool has its strengths, capabilities, and drawbacks in mapping demands of the user or the phenomenon under investigation. Popular scientific mapping software include CitNetExplorer, CiteSpace, Gephi, BibExcel, VantagePoint, and VOSviewer (Osei-Kyei et al., 2023). This study utilized VOSviewer (version 1.6.9), an open-source and user-friendly scientific software tool designed for mapping literature. VOSviewer was employed to visualize bibliometric networks and map the literature scientifically. The second phase of the research involved determining the best database to obtain bibliometric data on critical success factors in PPPs. The Web of Science database was chosen due to the extensive studies available. In the third phase, bibliometric data were extracted and analyzed from the Web of Science (WOS) database. Using the keywords of "public private partnership projects" and "critical success factors", a search was conducted in "title, abstract, and keywords" on WOS including all forms of publications (i.e., conferences, books, and journals, as well as documents) from any time, with the language limit to English. The search resulted with 419 publications, and the bibliometric data were downloaded as a plain text file. After importing the data into

VOSviewer, the analysis was carried out by constructing maps (networks) and tables. The findings of the analysis are presented and discussed in the following sections.

Results

This section presents the most notable bibliometric analysis results. Using the specified keywords, 419 references were retrieved, including 364 articles, 31 review articles, 24 proceedings papers, 5 book chapters, and 17 early access studies. Figure 2 shows the annual publication trend of research articles on critical success factors in PPP projects. As depicted in Figure 2, publications span from 2005 to 2024 (including the end of March), with the number of publications generally increasing over the years. The upward trend in publications on critical success factors in PPP projects suggests that more research in this area is likely in the coming years, underscoring the importance of identifying critical success factors.

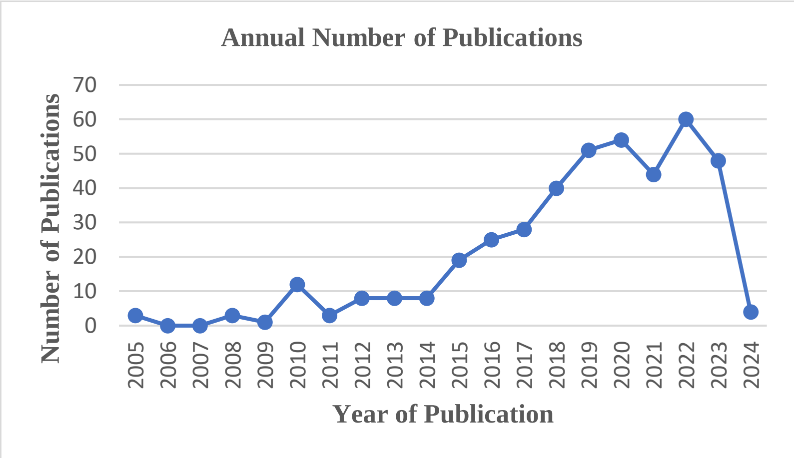

Figure 2: Annual number of publications.

Journals play a crucial role in disseminating research findings, and a thorough analysis of the top academic journals on critical success factors in PPP is essential to guide scholars and researchers regarding suitable platforms for publishing in this research area. For this purpose, the scientific map of prominent journals of critical success factors in PPP was examined. Journals with at least 5 published articles and more than 20 citations were taken into consideration. As shown in Table 1, 16 journals emerged as prominent in this field. The top significant research sources include International Journal of Project Management, Journal of Construction Engineering and Management, Construction Management and Economics, International Journal of Construction Management, and Journal of Facilities Management.

Keywords are vital for indexing research publications in databases as well as revealing the articles' primary ideas. The emerging keywords of critical success factors in PPP publications were retrieved and thoroughly analyzed, as shown in Figure 3. The results revealed that 972 author keywords were used, but it had some recurring items, such as ‘ppp’, ‘ppps’, ‘public private partnership (ppp)’ and ‘public private partnership’. This necessitated merging these phrases into one keyword. In addition, some keywords were combined under a title to obtain a more meaningful result, for instance, given countries were added under the keyword of ‘developing countries’: Ethiopia, Ghana, Nigeria, Tanzania, Uganda, China, Malaysia, Turkey, Vietnam, Indonesia. A thesaurus file containing these merged phrases was then constructed and imported into the software. Figure 3 was created by setting the minimum number of occurrences of keywords to 5. This method seeks to remove unnecessary expressions in text analysis, allowing for clearer and more relevant findings. As it can be seen in Figure 3, the keywords with larger nodes represent the most commonly used author keywords in PPP critical success factor studies. These keywords include 'public-private partnership (ppp)', 'developing countries', 'critical success factors (csf)', 'infrastructure', 'risk management', 'sustainability'. Additionally, keywords are grouped into clusters displayed in different colors. Clusters represent groups of keywords that are related and frequently occur together in the research articles. For example, "Red Cluster" is related to the management and implementation of infrastructure projects and services, which includes 'concession', 'contract', 'failure driver', 'infrastructure', 'literature review', 'projects', 'public service', 'public-private partnership (ppp)', 'risk', 'water services' keywords.

Table 1. Numerical analysis of prominent journals of critical success factor in PPP.

Journal	Number of articles	Citations	Average Citation	Total Link Strength
International Journal of Project Management	14	2248	161	413
Journal of Construction Engineering and Management	17	1124	66	239
Construction Management and Economics	8	621	78	141
International Journal of Construction Management	25	505	20	228
Journal of Facilities Management	12	447	37	178
Journal of Management in Engineering	16	445	28	101
Journal of Cleaner Production	6	420	70	29
Built Environment Project and Asset Management	18	391	22	158
Sustainability	27	353	13	147
Journal of Infrastructure Systems	12	312	26	61
Engineering Construction and Architectural Management	22	289	13	202
Journal of Civil Engineering and Management	7	231	33	69
Journal of Financial Management of Property and Construction	10	147	15	115
Journal of Engineering Design and Technology	10	122	12	49
Construction Innovation-England	5	75	15	45
Buildings	12	40	3	83

Cluster 1 (Red Cluster) - PPP Governance and Risk Management: Effective risk management supports project resilience and timely delivery, so this cluster addresses the importance of risk management in PPP projects for infrastructure development. It stresses the importance of literature reviews and governance structures established through contracts. It emphasizes the interconnectedness of contracts, concessions, risk management, and failure drivers all of which are crucial for ensuring project success and benefiting all stakeholders in PPPs.

Cluster 2 (Green Cluster) - Risk Management and Decision Analysis Frameworks: Collaboration between public and private sectors in PPPs necessitates effective risk management. This cluster focuses on managing and evaluating PPP projects effectively, emphasizing critical success factors and some project management techniques. Fuzzy Synthetic

Evaluation technique helps handle uncertainties and diverse stakeholder perspectives, while Structural Equation Modeling allows for analyzing complex relationships between variables, providing insights into their effects on project outcomes. Integrating these methodologies enhances decision-making, risk mitigation, and overall project success in PPPs.

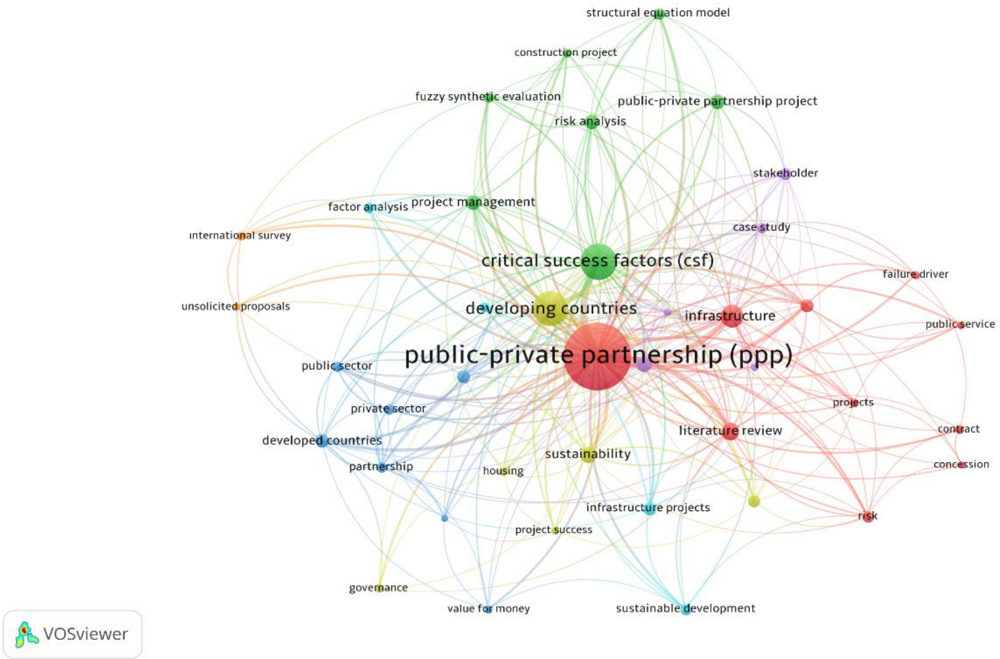

Figure 3: Network analysis of author keywords.

Cluster 3 (Blue Cluster) - Performance Management and Value in PPPs: Cluster 3 focuses on evaluating the performance and value derived from PPP projects, particularly in developed countries. In the context of PPPs, key performance indicator (KPI) evaluation, efficient procurement processes, exploring the partnership dynamics between the public and private sectors, achieving value, sustaining long-term partnerships with the private sector, ultimately benefiting the public through cost-effective and high-quality infrastructure and services are paramount for developed countries.

Cluster 4 (Yellow Cluster) - Sustainable Infrastructure Development in Developing Countries: In developing nations, PPPs play a vital role in advancing infrastructure. Transparent governance is key to mitigating risks, ensuring accountability, and fostering collaboration between the public and private sectors. This cluster examines governance structures and sustainability considerations within PPP projects, particularly in developing countries. Overall, governance, project success, sustainability, and robust risk management are critical components for the success of PPP projects in developing countries, collectively contributing to economic growth and enhancing living standards.

Cluster 5 (Purple Cluster): Risk Management and Stakeholder Engagement: Cluster 5 explores risk management strategies, stakeholder analysis techniques, and case studies within the construction industry, and underscores the importance of stakeholder collaboration and proactive risk management approaches to ensure project success. PPPs play a crucial role in infrastructure development, necessitating an understanding of various models like BOT, BOO, etc. Case studies provide invaluable insights into best practices and pitfalls to avoid, guiding stakeholders in efficient project implementation. Engaging stakeholders, including governments, investors, and communities, is essential for transparency and trust, managing diverse interests and expectations.

Cluster 6 (Cyan Cluster) - Risk Analysis for Sustainable Infrastructure Development: Risk factor analysis is crucial in PPPs for infrastructure projects, as it enables stakeholders to identify, assess, and mitigate risks. By understanding these critical risk factors, PPPs can enhance project viability, attract private investment, and promote sustainable development by integrating environmental and social considerations into project planning and design. Additionally, risk factor analysis facilitates stakeholder collaboration and decision-making, fostering transparency, accountability, and trust among public sector agencies, private investors, financial institutions, and local communities. This collaborative approach ensures the long-term resilience of infrastructure assets and maximizes their socio-economic benefits, contributing to overall economic growth and societal well-being. This cluster delves into the analysis of risk factors and sustainable development considerations in infrastructure projects.

Cluster 7 (Orange Cluster) - Innovations in PPPs: Unsolicited proposals are pivotal in enhancing the success of Public-Private Partnerships (PPPs) by introducing innovation, accelerating project development, and fostering stakeholder engagement. This cluster explores international perspectives on PPPs and the implications of unsolicited proposals in project development. It involves conducting international surveys to gather insights and best practices from diverse contexts. Additionally, it addresses the challenges and opportunities associated with unsolicited proposals in PPP procurement processes. Together, these mechanisms enhance due diligence, foster stakeholder engagement, and drive policy reform by promoting transparency, efficiency, and the adoption of emerging technologies and approaches.

The collaboration analysis of leading researchers may inform scholars about experienced researchers open to possible collaboration in the future. Figure 4 shows the leading researchers of PPP critical success factor studies and their collaboration links. A researcher must have at least five publications and 20 citations to be included in the figure.

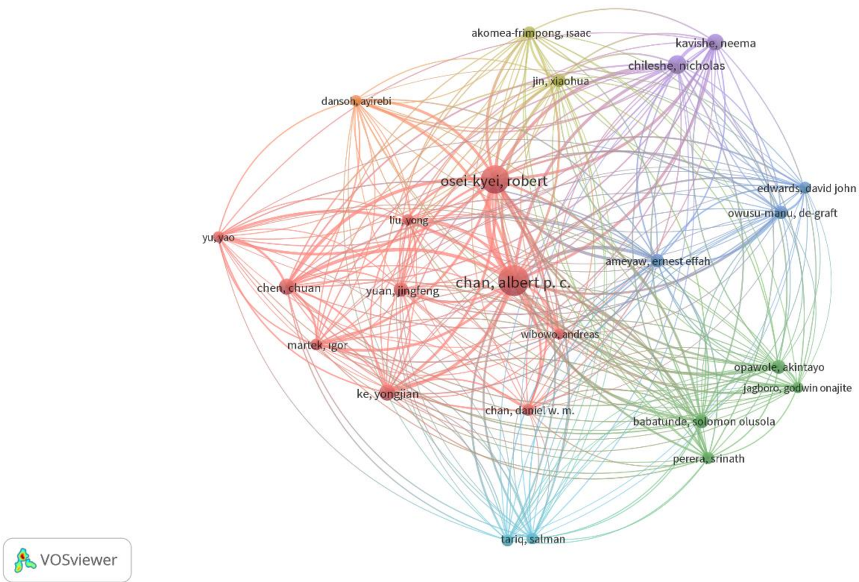

Figure 4: Bibliographic coupling network of authors.

To understand the value of previous research investigations, the number of citations that an article receives is a direct indicator of its impact. Table 2 lists the top eight most influential articles in this area.

Table 2. High impact articles on critical success factor in PPP.

Reference	Article	Citations	Links	Total Link Strength
(Li et al., 2005)	Critical success factors for PPP/PFI projects in the UK construction industry	468	64	397
(Osei-Kyei & Chan, 2015)	Review of studies on the Critical Success Factors for Public-Private Partnership (PPP) projects from 1990 to 2013	467	57	2626
(Zhang, 2005)	Critical success factors for public-private partnerships in infrastructure development	458	73	673
(Cui et al., 2018)	Review of studies on the public private partnerships (PPP) for infrastructure projects	271	24	2503
(Xu et al., 2010)	Developing a risk assessment model for PPP projects in China - A fuzzy synthetic evaluation approach	270	18	467
(Chan et al., 2010)	Critical Success Factors for PPPs in Infrastructure Developments: Chinese Perspective	260	53	1417
(Tang et al., 2010)	A review of studies on Public-Private Partnership projects in the construction industry	259	22	722
(Hwang et al., 2013)	Public private partnership projects in Singapore: Factors, critical risks and preferred risk allocation from the perspective of contractors	252	33	468

The identification of leading countries is crucial for understanding the active contributors to PPP research. When the countries were examined, initially 63 countries were obtained where 26 countries included in the mapping that satisfy the criteria of at least 5 published articles and 20 citations. Figure 5 displays the top productive countries where China, Australia, England, and Singapore are at the top of the list when countries are ranked by the number of citations.

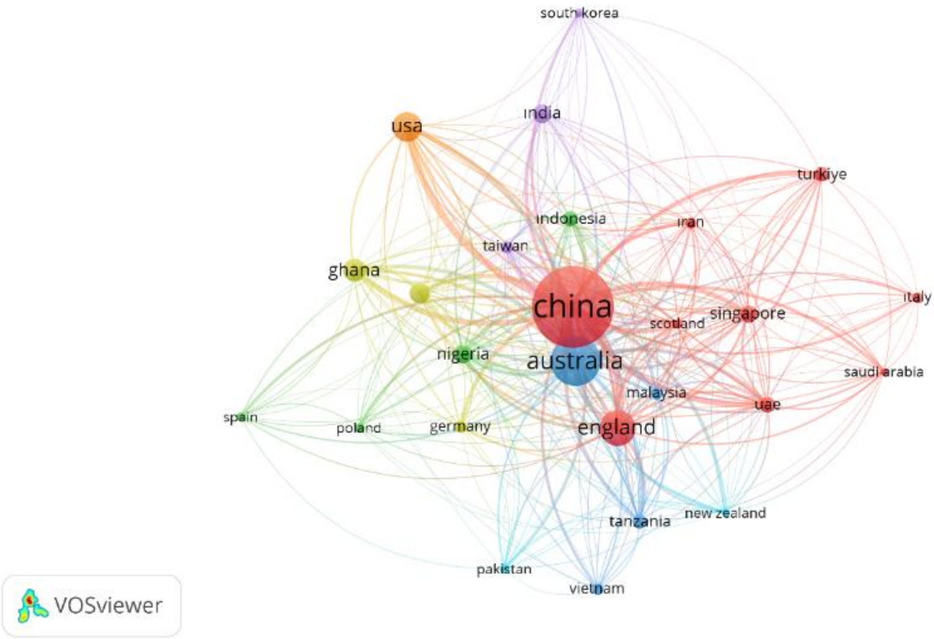

Figure 5: Mapping of active countries of PPP critical success factor studies.

Conclusion

This study conducts a bibliometric review on critical success factors in PPP projects by examining 419 research studies. The study provides significant background information to researchers, stakeholders, policy makers and funders, identifying the dominant focus areas in critical success factors research in PPP projects, and highlighting leading authors. This initial screening of the domain underlines valuable findings for further research in this area. However, the study is oriented to a single database and acknowledges the inability to review all studies manually that hinders the risk of including some unrelated studies or possibility that overlooking the critically important ones. Additionally, certain research themes may have been overlooked due to the prevalence of repeated keywords. Therefore, further research should incorporate other databases and clean the obtained data before proceeding with further analysis.

References

Chan, A. P. C., Lam, P. T. I., Chan, D. W. M., Cheung, E., & Ke, Y. (2010). Critical success factors for PPPs in infrastructure developments: Chinese perspective. *Journal of Construction Engineering and Management*, *136*(5), 484-494.

Cui, C., Liu, Y., Hope, A., & Wang, J. (2018). Review of studies on the public–private partnerships (PPP) for infrastructure projects. *International Journal of Project Management*, *36*(5), 773-794.

Hwang, B. G., Zhao, X., & Gay, M. J. S. (2013). Public private partnership projects in Singapore: factors, critical risks and preferred risk allocation from the perspective of contractors. *International Journal of Project Management*, *31*(3), 424-433.

Li, B., Akintoye, A., Edwards, P. J., & Hardcastle, C. (2005). Critical success factors for PPP/PFI projects in the UK construction industry. *Construction Management and Economics*, *23*(5), 459-471.

Mulyani, S. (2021). Critical success factors in public-private partnership. *Journal of Accounting Auditing and Business*, *4*(1), 81.

Osei-Kyei, R., & Chan, A. P. C. (2015). Review of studies on the critical success factors for public-private partnership (PPP) projects from 1990 to 2013. *International Journal of Project Management*, *33*(6), 1335-1346.

Osei-Kyei, R., Jin, X., Nnaji, C., Akomea-Frimpong, I., & Wuni, I. Y. (2023). Review of risk management studies in public-private partnerships: a scientometric analysis. *International Journal of Construction Management*, *23*(14), 2419-2430.

Tang, L. Y., Shen, Q., & Cheng, E. W. L. (2010). A review of studies on public-private partnership projects in the construction industry. *International Journal of Project Management*, *28*(7), 683-694.

Wang, H., Xiong, W., Wu, G., & Zhu, D. (2018). Public–private partnership in public administration discipline: a literature review. *Public Management Review*, *20*(2), 293-316.

Xu, Y., Yeung, J. F. Y., Chan, A. P. C., Chan, D. W. M., Wang, S. Q., & Ke, Y. (2010). Developing a risk assessment model for PPP projects in China-A fuzzy synthetic evaluation approach. *Automation in Construction*, *19*(7), 929-943.

Zhang, X. (2005). Critical success factors for public–private partnerships in infrastructure development. *Journal of Construction Engineering and Management*, *131*(1), 3-14.

Identifying Factors Affecting Productivity in Architectural Design Offices

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Abstract

Architectural design offices (ADOs), which are the producers of design projects in the rapidly developing construction industry, need not only to work hard, but also to work productively in order to survive in today's competitive market. The ability to complete a task, generate a product, or accomplish an objective while making the best use of available resources is referred to as productivity. Workloads in ADOs are frequently heavy, challenging and need to be completed in a short period of time. Furthermore, this industry's projects frequently call for swift adaptation to constantly shifting circumstances and client expectations. In order to maintain success and keep up with the industry's rapid pace, it is vital that ADOs ensure productive work. Thus, this study aims to identify the factors affecting productivity of ADOs. As a result of the research, it was concluded that there is a gap in the literature on the subject. To identify the factors and prioritize them, interviews were held with the experts who are owners of ADOs with at least 10 years of experience. Following expert interviews, the study sheds light on key areas of concern about ensuring productive work in ADOs for future studies.

Keywords: *productivity, architectural design offices, construction industry, organization.*

Introduction

The rapid advancement of technology is shifting people's expectations and demands, affecting various sectors, including construction. The construction industry is benefiting from these technological developments, leading to increased project complexity and heightened competition among stakeholders. ADOs, key players in this industry, must produce high-quality projects while efficiently utilizing resources to remain competitive. For ADOs to successfully manage complex projects and meet modern expectations, maintaining productivity is essential, which offers ADOs a competitive advantage, satisfied clients and long-term success. Offices may complete more work in less time and with fewer resources as their productivity rises. The resources could be any combination of labor, capital, materials, energy, and information (Jurison, 2002). This improves client satisfaction and encourages repeat business by ensuring that projects are completed on time and within budget. Furthermore, productive work gives the office a competitive edge and improves its reputation. Additionally, a productive workplace increases staff morale and encourages innovation, which raises project quality and contributes to the office's long-term success.

Improving ADO productivity requires identifying the factors that influence it. A thorough literature review revealed a knowledge gap on this subject. In regard to this backdrop, the aim of the research is to shed light on the knowledge gap in the literature by identifying and prioritizing the factors affecting productivity in ADOs. To achieve this, expert interviews were held. Responses obtained from the experts who are managers of selected ADOs with at least 10 years of experience in the sector were analyzed, resulting in a total of 21 factors identified.

Literature Review

Concept of Productivity: It is crucial to understand that there are various definitions of productivity, each of which is appropriate in a particular situation (Björkman, 1992). The definition of productivity by Sudit (1984) is typically expressed in terms of ratios between inputs and outputs, which contains the classical definition of productivity in the literature. Jurison (2002) says that productivity is a measure of how well resources (which can be any combination of labor, capital, materials, energy, and information) are used to produce different types of goods and services. Productivity, defined as "the ratio of output to input" essentially asks "What did people produce for what they used?" (Moore & Moore, 1981).

Concept of Organization: An organization involves the logical arrangement of the efforts of several individuals to attain a shared and clearly defined objective, achieved through the distribution of tasks and roles, as well as a hierarchical structure of authority and accountability (Schein, 1980). Organizations shape the modern world by acting as the backbone of many sectors and businesses (Mintzberg, 1979). They become such an integral part of our lives that we can scarcely imagine life without them and many of the goals we set for ourselves as a society can be achieved through organizations (McFarland & Gomez, 2016).

Improving Organizational Productivity and Factors Affecting It: Improved productivity essential for an organization to develop, grow, earn and ultimately ensure the organization's survival (Gaur, 2012). Productivity improvement guarantee that the products and services are created and provided in the most efficient way possible (Sahni, 2016). There are many factors that affect the improvement of productivity in an organization. As a result of the literature review, factors that have been mentioned in the literature by at least three different authors were identified. Factors that are not described by the same name but describe the same situation are classified under the same heading. The seven factors identified and the effects of these factors on the productivity improvement of an organization are explained in Table 1.

Table 1. Explanations of 7 factors affecting organizational productivity.

Factor Name	Explanation	References
Communication	Setting clear and realistic goals, along with effective communication strategies, enhances organizational productivity by ensuring proper information flow and fostering employee engagement and contribution.	Moore & Moore, 1981; McTavish et. al., 1996; Gaur, 2012
System of management	An organization's ability to increase productivity hinges on effective management, strategic thinking, leadership behavior, corporate culture, communication processes, and technology management, with productivity being crucial for organizational success and dependent on realistic, achievable goals set by management.	McTavish et. al., 1996; Islam, 2021; Khan et. al., 2023
Employee’s performance and productivity	Employers should focus on elements that enhance employee growth and performance, as employee productivity is crucial for	Khan et. al., 2023; Kumar, 2013; Lee, 2004.

	organizational success and can provide a competitive advantage, making it a top priority for any organization.	
Teamwork	It is one of the main factor influencing productivity, leading to a competitive edge, higher margins, better management, increased production value, enhanced job satisfaction and improved utilization of employee skills, thereby boosting organizational productivity.	Khan et. al., 2023; Jiang et. al., 2018; Agarwal & Adjirackor, 2016.
Motivation and job satisfaction	Organizations should aim to ensure staff satisfaction because happy workers are productive workers, with improved performance and productivity resulting from motivational efforts that emphasize long-term benefits.	Kumar, 2013; Islam, 2021; Pinder, 1984.
Training and development	Development and training are vital for organizational productivity because employees become more productive and successful when they acquire new skills and knowledge, enhancing both organizational productivity and return on investment, while also boosting employee motivation to perform at their best.	Ahmad et al., 2016; Sookdeo, 2020; Khan et al., 2023.
Employee commitment	All efforts to enhance productivity hinge on the willingness of employees at all levels, influenced primarily by their commitment to the job, as committed employees exhibit greater capability, passion, belief in organizational goals, and performance, thereby working more to boost organizational productivity.	Guy, 1992; Lee, 2004; Altaf & Naqvi, 2013.

Factors Affecting Productivity in ADOs: ADOs have large, difficult workloads that must be finished quickly and projects in this sector usually require quick adjustments to continually changing conditions and customer demands. To be competitive and meet the industry's fast-paced demands, ADOs must ensure productive work. Contrary to the importance of the productive work in ADOs, it is thought that there is not enough attention in the literature to contribute to the more productive functioning. Although ADOs are also organizations; every organization has different dynamics and productivity can mean a different situation for each of them. Therefore, it would be more useful to examine productivity and identify factors affecting it specifically for ADOs (i.e., the aim of the study).

Research Method

In order to identify and prioritize factors affecting productivity in ADOs, expert interviews were held. The selected experts are the managers of seven ADOs that have experience in the industry for at least 10 years. After collecting the data from interviews, both content and statistical analyses were conducted to achieve the aim of the study.

First of all, content analysis applied to the responses of the open-ended question directed at seven office managers, which was, "In your opinion, what are the factors affecting productivity in ADOs?". As a result of content analysis, a total of 21 factors have been extracted. After content analysis, the mean score ranking technique and reliability analysis was applied to prioritize and identify critical factors among the 21 factors extracted. The factors provided by seven office managers were rated by them using a 7-point Likert scale with “1” meaning “not strong factor” and “7” meaning “very strong factor”.

In order to measure a relationship between literature review and experts' thoughts, also productivity in organizations and productivity in ADOs, the extent to which the seven factors affecting organizational productivity obtained from the literature review correspond to the "factors affecting productivity in ADOs" identified by ADO managers has been analyzed. After this analysis, the mean score ranking technique and reliability analysis was applied to prioritize and identify critical factors among the seven factors obtained from literature. The seven factors affecting organizational productivity obtained from literature were rated by them using a 7-point Likert scale with “1” meaning “not strong factor” and “7” meaning “very strong factor”.

Reliability needs to be assessed in order to ascertain the internal consistency of data that use the Likert scale (Nunnally and Bernstein, 2007). Cronbach's alpha (α) coefficient was utilized by using SPSS (Statistical Package for the Social Sciences) software to assess the validity and statistical reliability of the responses provided by the respondents. The acceptable reliability level was determined to be 0.7, with the α coefficient values ranging from "0" to "1" (Cronbach, 1951; Tavakol and Dennick, 2011).

In the mean score ranking technique, the significance of normalized mean values (NMVs) lies in their ability to ascertain the criticalities of the factors. NMVs are determined for each element using the NMV formula which is given below. A factor is deemed to be a critical factor (CF) if its NMV is more than 0.5 (Liao and Teo, 2017; Zhou et. al., 2019).

$$NMV = \frac{(mean\ of\ F - lowest\ mean)}{(highest\ mean - lowest\ mean)} \tag{1}$$

NMV: normalized mean value, F: factor

Findings

In the first step, as a result of the content analysis of responses to the question “In your opinion, what are the factors affecting productivity in ADOs?”, a total of 21 factors were extracted. Narratives from responses expressing similar thoughts have been grouped under the same factor heading (for another example, responses such as “ergonomy of the office” and “lighting and ventilation of the office” have been combined under the heading “physical facilities of the office”). These 21 factors and the definitions produced according to the answers are presented in Table 2.

Table 2. Explanations of 21 factors that affect productivity in ADOs.

Factor Name	Explanation
Communication	The transfer of information, ideas, feelings, or instructions among different individuals, departments, or stakeholders through written, verbal, visual, or various tools.
Employee knowledge and experince	Collective understanding, skills, expertise, and practical know-how that an individual brings to their role.
Organizational skills of management	Ability of managers to efficiently plan, coordinate, and oversee various aspects of office’s operations to achieve its goals effectively.
Interest in the project	Enjoying the project being worked on, feeling curious, and consequently, having the desire to enhance the design.
Teamwork	Collaboration among architects, designers, engineers, and other professionals to collectively create architectural solutions.
Physical facilities of the office	The layout, furniture, equipment, technology, and amenities available for use by employees and visitors within the office space that support its operations and functions.
Performance of individuals	Individual’s ability to effectively carry out their assigned tasks and responsibilities in alignment with organizational goals and standards.
Employee commitment	The level of dedication, loyalty, and engagement that an individual demonstrates towards office and its goals.
Economic satisfaction of employees	The level of contentment or fulfillment that employees experience regarding their financial compensation and benefits provided by their employer.

Variable customer demands	Frequently shifting and fluctuating requirements, expectations, and preferences that clients may have when seeking architectural services.
Manager's attitude towards employees	The manner in which a manager perceives, interacts with, and treats their subordinates or team members.
Technical infrastructure of the office	The array of technological resources, systems, and equipment utilized to support the office's operations and architectural design processes.
Motivation	The drive, enthusiasm, and commitment of individuals within the architectural profession to perform their work effectively and achieve professional and organizational goals.
Customer satisfaction	The level of contentment or fulfillment experienced by clients who have utilized the services of the office.
Involvement of the manager in the project process	The participation and engagement of the manager in various activities such as design process and decision-making within the office.
Customizable working conditions	The flexibility and adaptability of the work environment and policies to accommodate the diverse needs of employees within the office.
Continuity in the team	The consistency and stability of the team members working together on architectural projects over time.
Limited time periods	Constraints or deadlines within which architectural projects must be completed or specific tasks must be accomplished.
Similar generation	Having individuals of similar age groups or from the same generation working within the office.
Conflict between architectural education and industry	Misalignment or discrepancy between the skills, knowledge, and expectations taught in architectural education programs and the actual demands and practices of the architecture industry.
Stress management	The strategies, policies, and practices implemented within the office to help employees effectively cope with and alleviate stressors associated with their work.

In the second step, it was analyzed how many different office managers mentioned each factor and the results are presented in Table 3.

Table 3. 21 factors that affect productivity in ADOs.

Factor Name	Respondents	Number of Mention						
		1	2	3	4	5	6	7
Communication	1, 2, 3, 4, 5, 7						*	
Employee knowledge and experience	2, 3, 4, 5, 6					*		
Organizational skills of management	1, 3, 4, 6, 7					*		
Interest in the project	1, 2, 5, 7				*			
Teamwork	1, 3, 4, 7				*			
Physical facilities of the office	1, 2, 3			*				
Performance of individuals	3, 5, 6			*				
Employee commitment	1, 4, 7			*				
Economic satisfaction of employees	2, 3, 7			*				
Variable customer demands	2, 6, 7			*				
Manager's attitude towards employees	2, 5		*					
Technical infrastructure of the office	1, 6		*					
Motivation	4, 6		*					
Customer satisfaction	5, 6		*					
Involvement of the manager in the project process	3, 7		*					
Customizable working conditions	2, 6		*					
Continuity in the team	5, 7		*					
Limited time periods	1	*						
Similar generation	2	*						

Conflict between architectural education and industry	5	*						
Stress management	7	*						

As seen in Table 3, there has not been a factor mentioned by all seven office managers. The communication factor has been the most frequently mentioned factor, which is mentioned by six different managers.

In the third step, mean score ranking technique was conducted to identify the critical factors (CFs) among 21 factors. When the findings of this study are analyzed, it is determined that among the 21 factors, 9 of them are determined as CFs (factors with NMV ≥ 0.50). The means, standard deviations (Sd), normalized mean values (NMV) and rankings of factors are presented in Table 4.

Table 4. Ranking of factors affecting productivity in ADOs.

Factor Name	Mean	Sd	NMV	Rank
Communication (CF)	6,00	1,00	1,00	1
Employee knowledge and experience (CF)	5,29	1,70	0,82	6
Organizational skills of management (CF)	5,71	0,95	0,93	2
Interest in the project	3,86	1,46	0,44	14
Teamwork (CF)	4,29	0,95	0,56	8
Physical facilities of the office (CF)	4,43	1,13	0,59	7
Performance of individuals (CF)	5,57	1,13	0,89	4
Employee commitment (CF)	5,29	0,76	0,82	5
Economic satisfaction	4,00	1,73	0,48	12
Variable customer demands (CF)	4,29	1,38	0,56	9
Manager's attitude towards employees	3,71	1,50	0,41	15
Technical inrastructure of the office	3,86	0,70	0,44	13
Motivation (CF)	5,71	1,11	0,93	3
Customer satisfaction	3,14	1,22	0,26	18
Involvement of the manager in the process	3,29	0,76	0,30	17
Customizable working conditions	4,00	1,16	0,48	11
Continuity in the team	3,29	0,76	0,30	17
Limited time periods	4,00	1,00	0,48	10
Similar generation	2,14	1,22	0,00	20
Conflict between architectural education and industry	2,43	0,98	0,07	19
Stress management	3,57	0,79	0,37	16

CF: critical factor, Sd: standard deviation, NMV: normalized mean value

As seen in Table 4, the results indicate that the range of factors mean values is 2,14 to 6,00. Out of the 21 factors in this group, the results show that 9 factors have normalized values greater than 0.50 and are therefore assumed to be CF: communication, employee knowledge and experience, organizational skills of management, teamwork, physical facilities of the office, performance of individuals, variable customer demands, and motivation. With a mean value of 6,00, "communication" is found to be the most critical factor affecting productivity in ADOs. Similar generation is found to be the least critical factor with a mean value of 2,14. When ranking among factors that have the same mean value, the factor with lower standard deviation value from the other has been positioned above.

The Cronbach α coefficient was used in a reliability analysis to ascertain the internal consistency of the interviews. The data set's α coefficient for the 21 factors that affect productivity in ADOs is calculated “0,792” which is higher than the minimal requirement of “0.7” (Tavakol and Dennick, 2011).

Finally, the degree to which the seven factors affecting organizational productivity obtained from the literature review correspond to the "factors affecting productivity in ADOs" identified by ADO managers has been analyzed in order to assess the relationship between the literature review and expert interviews, as well as productivity in organizations and productivity in ADOs. Factors that describe the same situation, even if named differently, have been considered as the same factor (for example, organizational skills of management and system of management factors have been considered as the same factor). The information about how many different office managers have mentioned each factor obtained from literature is presented in Table 5.

Table 5. The relationship between responses and factors affecting organizational productivity.

Factor Name	Respondents	Number of Mention						
		1	2	3	4	5	6	7
Communication	1, 2, 3, 4, 5, 7						*	
System of management	1, 3, 4, 6, 7					*		
Teamwork	1, 3, 4, 7				*			
Job satisfaction	1, 2, 5, 7				*			
Performance and productivity of employees	3, 5, 6			*				
Employee commitment	1, 4, 7			*				
Training and development	-							

As seen in Table 5, there has not been a factor mentioned by all seven office managers. The communication factor has been the most frequently mentioned factor, which is mentioned by six different managers. It can be stated that there is a correlation between the factors affecting productivity in ADOs specified by the participating ADO managers (i.e., experts) and the factors affecting organizational productivity mentioned in the literature. But, suprisingly, although FL7 (training and development) is included in the literature as an important factor affecting organizational productivity, it was not put forward as a factor affecting productivity in ADOs by any ADO managers who participated in the interviews. This might indicate managers of ADOs undervalue FL7 (training and development) factor; the nature of the architectural design requires a master apprentice approach which is also a form of “training and development” by on job training. So we can assert that “training and development” is a built-in factor for ADOs.

Conclusion

The main objective of this study is to contribute to the gap in the literature regarding the factors affecting productivity in ADOs. Through conducted research, a deficiency in the literature concerning this subject has been identified. To achieve the aim of the study, seven ADOs with at least 10 years of industry experience were selected and interviews were held with office managers. Upon analyzing the thoughts of managers, 21 factors were identified. These 21 factors were analyzed using mean score ranking and 7-point Likert scale techniques to determine critical ones (i.e., CFs) and rank them based on their impact. When the findings of this study are analyzed, it is determined that among the 21 factors, 9 of them are determined as CFs (factors with NMV $\geq$ 0.50): communication, employee knowledge and experience, organizational skills of management, teamwork, physical facilities of the office, performance of individuals, variable customer demands and motivation. When examining the intensity of the impact, with a mean value of 6,00, "communication" is found to be the most critical factor affecting productivity in ADOs. “Similar generation” is found to be the least critical factor with a mean value of 2,14.

It could be concluded that there is a strong relationship between the organizational productivity elements indicated in the literature and the productivity factors in ADOs as reported by the participating ADO managers (communication, system of management, teamwork, job satisfaction, performance and productivity of employees, employee commitment). Surprisingly, however, none of the ADO managers who took part in the study mentioned “training and development”, despite the fact that it is mentioned in the literature as a significant element influencing organizational productivity. This may be due to training and development being an innate part of the architectural design process. It should be noted that the results obtained from this study are limited to the experiences of the seven ADO managers who participated in the interviews. In the future, new and more extensive studies on the subject will make the findings of this study more meaningful and contribute to the expansion of the literature in productivity and organization of ADOs.

References

Agarwal, S. & Adjirackor, T. (2016). Impact of Teamwork on Organizational Productivity in Some Selected Basic Schools in The Accra Metropolitan Assembly. *European Journal of Business, Economics and Accountancy*, 4(6), 40-52.

Ahmad, N., Khan, S. & Ali, F. (2016). An investigation of workplace environment in Karachi textile industry towards emotional health. *Journal of Independent Studies and Research,* 14(1), 63-78.

Altaf, A. & Naqvi, I.H. (2013). Employee commitment enhances team efficacy: Empirical evidence on telecom sector of Pakistan (Lahore). *World Applied Sciences Journal*, 22(8), 1044-1049.

Björkman, M. (1992). What is Productivity. *IFAC Proceedings Volumes,* (25), 203-210.

Cronbach, L. J. (1951). Coefficient alpha and the internal structure of tests. *Psychometrika*, 16, 297-334.

Gaur, V. (2012). Holistic Approach to Productivity. *European Journal of Business and Management*, 4(15), 88-94.

Guy, M.E. (1992). Managing People. *Public Productivity Handbook*, edited by Marc Holzer, 307-320. New York: Marcel Dekker.

Islam, M.S. (2021). Motivational Intervention in Productivity Improvement. *Bangladesh Journal of Public Administration*, 8(1-2), 39-67.

Jiang, Y., Xiao, L., Jalees, T., Naqvi, M. H. & Zaman, S. I. (2018). Moral and ethical antecedents of attitude toward counterfeit luxury products: Evidence from Pakistan. *Emerging Markets Finance and Trade*, 54(15), 3519-3538.

Jurison, J. (2002). Productivity. *Encyclopedia of Information Systems*, (3), 517-528.

Khan, S., Khan, M.I., Rais, M. & Aziz, T. (2023). Organizational Productivity: A Critical Analysis of the Impact of Employee Motivation. *Reviews of Management Sciences*, 5(1), 13-37.

Kumar, H. (2013). Employee Productivity Management: Maladies and Remedies. *European Journal of Business and Management*, 13(4), 235-240.

Lee, S. (2004). Moving Forward to Employee Commitment in the Public Sector: Does it Matter? *International Review of Public Administration*, 8(2), 13-24.

Liao, L. & Teo, E. A. L. (2017). Critical success factors for enhancing the building information modeling implementation in building projects in Singapore. *Journal of Civil Engineering and Management*, 23(8), 1029-1044.

McFarland, D.A. & Gomez, C.J. (2016). Organizational Analysis. *Stanford University*.

McTavish, R., Gunasekaran, S., Goyal, S. and Yli-Olli, P. (1996). Establishing a strategic framework for improving productivity. *Integrated Manufacturing Systems*, 7(4), 12-21.

Mintzberg, H. (1979). The Structuring of Organizations. *Pearson*.

Moore, L.B. & Moore, C.B. (1982). Productivity and Organizational Management. In: *Productivity Analysis*, 1(8), 149-165.

Nunnally, J. C. & Bernstein, I. H. (2007). *Psychometric Theory*. McGraw-Hill, New York, NY.

Pinder, C.C. (1984). *Work Motivation; Theory, Issues, and Applications.* Foresman and Company, Glenview.

Sahni, A. (2016). Methods of Productivity Improvement: A Literature Review. *International Journal of Research in Engineering and Technology*, 5(10), 112-118.

Schein, E. H. (1980). *Organizational psychology* (3d ed.). Prentice-Hall.

Sookdeo, B. (2020). From defining to measuring productivity: a coherent leadership strategy for effectiveness. *Strategic Direction*, 36(4), 4-6.

Sudit, E. (1984). The Productivity Concept: Definition, Measurement and Managerial Importance. In: Productivity Based Management. *Studies in Productivity Analysis*, (5), 1-17.

Tavakol, M. & Dennick, R. (2011). Making sense of Cronbach's alpha. *International Journal of Medical Education*, 2, 53-55.

Zhou, Y., Yang, Y. & Yang, J. B. (2019). Barriers to BIM implementation strategies in China. *Engineering, Construction and Architectural Management*, 26(3), 554-574.

An Investigation into Sustainable Construction Project Management in the Built Environment

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Abstract

The built environment (BE) is at risk from greenhouse gas emissions, energy consumption and resource depletion. Therefore, sustainability, which provides improvement in triple bottom lines (TBL) (environmental, social, economic), has become the focus of governments, professionals, and academics worldwide. Many sustainability-oriented-steps have been taken worldwide (e.g., The Paris Climate (2050), The Green Deal) that support all industries globally to take action to fight against the crisis affecting TBL. The construction industry (CI) implements various projects (e.g., infrastructure, superstructure, industrial) to establish BE. While CI increases social and economic development by establishing BE through various projects, CI also creates a negative impact on the environment, accounting for 40% of global CO_2 *emissions. The sustainable construction project management (CPM) plays a major role in CI, which enhance the establishment of BE in line with TBL. Therefore, this study aims to examine how sustainability is addressed in CPM literature. This study reviewed the sustainability in CPM literature. The findings emphasize that sustainability should be considered as a holistic approach with TBL. Additionally, addressing sustainability in different industries highlights the existence of industry-based sustainable development. However, there is a lack of studies in addressing sustainability in CPM to establish sustainable BE. This study may be useful to academics and professionals working sustainability in CPM.*

Keywords: *construction project management, sustainability, sustainable construction project management.*

Introduction

The impact of non-green industrial development, use of non-green technology and humans on the environment has reached harmful levels and continues to worsen rapidly. Minimizing environmental degradation has led to a search for a balance between nature and development; therefore, it has pioneered an approach that considers all impacts on people and living things, uses resources to meet today's needs, and considers the needs of future generations, in other words, pioneering to Sustainable Development. (Yıldız et al., 2018). The architecture, engineering, and construction industry (AEC) differs from other product-oriented service industries with its unique features (e.g. unique project, project-based production, long supply chain management, involvement of different professionals) (Tuz & Sertyeşilışık, 2020). AEC offers a variety of construction projects that enhance the creation of the built environment that can meet all today's needs and consider future generations (Tuz & Sertyeşilışık, 2023). Accordingly, AEC plays an important role in improving the quality of life, ensuring economic development and environmental concern (Tuz & Sertyeşilışık, 2023). The AEC industry improves the creation of the built environment and contributes to social and economic development through the employment opportunities it provides (Tuz & Sertyeşilışık, 2020). However, as an industry, it is among the industries that contribute to the most degradation with its environmental impacts; globally, AEC accounts for 40% of CO2 emissions, produces 25% of solid waste, and consumes more than 30% of natural resources (Benachio et al., 2020). Since construction projects have a long project-based supply chain created with the participation of many professionals (designers, suppliers, construction companies), the requirements and uncertainties differ and increasing in every stage of construction projects. Integrating sustainability into every stage of construction projects can increase the sustainable performance of construction projects in line with the TBL approach and ensure the creation of a sustainable built environment (Tuz & Sertyesilışık., 2021). Adhering to traditional construction project management, especially in complex design projects, is insufficient to fulfill sustainable requirements such as compliance with environmental standards and commitment to social responsibility in line with sustainable development goals (Ershadi & Goodarzi, 2021). To achieve sustainable development goals in AEC industry, this necessitates a transition from traditional construction project management to sustainable construction project management that protects human and natural resources, creates a green circular economy (Ershadi & Goodarzi, 2021). Although sustainability and the implementation of sustainable development goals are of great importance in the construction industry, studies focusing on sustainable construction project management and the implementation of TBL as a holistic approach in construction project management are limited. There are several examples focusing on sustainable construction project management: The Children and Youth Universe project in Denmark, which includes a kindergarten and nursery, aimed to integrate sustainable development goals into the construction project management decision process and aimed to achieve Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) gold certification (Gade et al., 2023). This study aims to examine how sustainability is addressed in the construction project management literature. This study is structured as follows: after the research methodology presented in section 2, the findings are presented in section 3, followed by the conclusion in section 4.

Methodology

This study aims to examine how sustainability is addressed in the construction project management literature with a holistic TBL approach. Structure literature review, which allows a clear examination of the existing research (Tuz & Sertyeşilışık, 2018), is used as the research methodology. Figure 1 summarizes the research methodology and the process of research. This study methodology is based on the research methodology of Tuz and Sertyeşilışık (2018) and structured on 4 consecutive steps.

Determining the purpose of this study is followed by selecting keywords to find existing research articles published in Elsevier (www.sciencedirect.com) in the first step of the research methodology. Content analysis that provides evaluation systematically of the existing studies published in a time range is applied for examining the existing research articles (Tuz & Sertyeşilışık, 2018). The time range covers the period from 2018 to the first quarter of 2024. Time period is classified as pre-pandemic, pandemic period, and post-pandemic (Figure 2). The database is searched based on keyword combinations such as "Sustainability" and "Construction project management" using the Boolean Operator (AND) in the Title, Abstract and Keywords. As a result of the research, 52 research articles were found, as shown in figure 2, the majority of which were published in the post-pandemic period. In the third stage of this study, descriptive analysis is applied to determine the primary focus points of existing studies. After the focus point is determined, irrelevant studies are eliminated, and the remaining studies are classified according to journals, publication year, geographical distribution, and focus point.

The overview of research methodology

Type of Analysis	Qualitative
Search Engine	Elsevier (www.sciencedirect.com)
Keywords	"Sustainability" AND "Construction Project Management"
Search in	Title, Abstract, Keywords
Time Period	2018-2024
Language	English
Type	Research articles

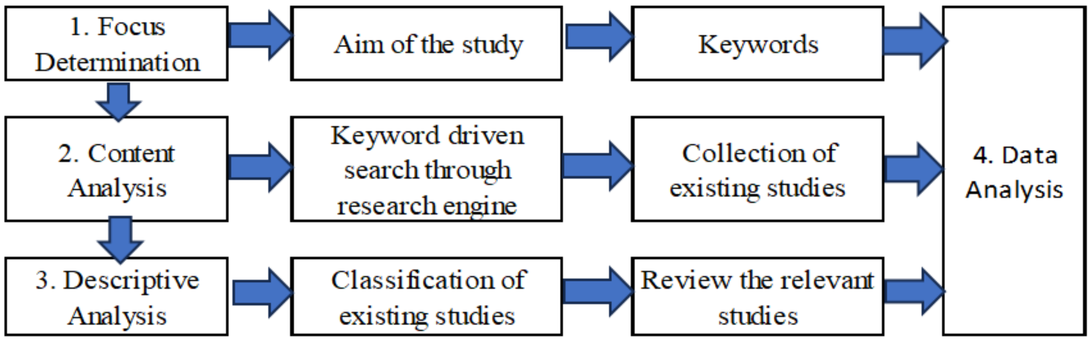

Figure 1: Research methodology the process of the research.

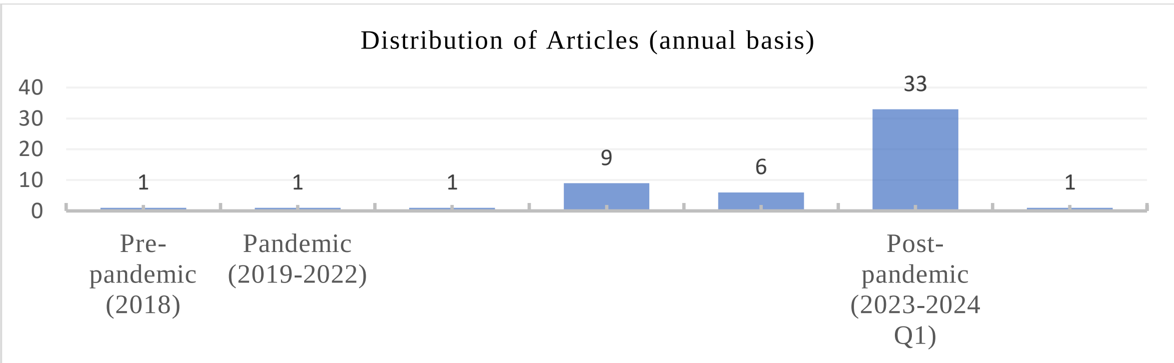

Figure 2: Distribution of articles (annual basis).

Content Analysis

In the first stage of the literature analysis, 52 research articles obtained from the research engine were published within the specified period. In-depth analysis was provided to find articles relevant to the main objective of this study. As a result, after excluding the 34 articles,18 articles formed the sampling frame.

The time range were classified in three different groups as pre-pandemic, pandemic, and post-pandemic period. There have been limited publication (1 research paper in 2018) in the pre-pandemic period, while between 2019 and 2022, there have been an increase in number of articles in pandemic period (8 research articles). Post-pandemic period, which covers the time between 2023 and first quarter of 2024, has the highest number of articles, especially 10 articles published in 2023. The majority of research articles in the sampling frame were published in 4 different journals: Journal of Building Engineering (22%), Alexandria Engineering Journal (11%), Developments in the Built Environment (11%) and International Journal of Project Management (11%). The remaining articles were distributed among 8 articles with the same percentages (6%) (Table 1).

The geographical distribution of the 18 research articles is shown in figure 3. Egypt makes the largest contribution to the total of existing articles suitable for the purpose of this study, with 22%, followed by China (11%), the UK (11%), and Jordan (11%). The remaining articles are distributed in 8 different countries with a contribution of 6%.

Table 1. Journal list.

Journal Name	**n**	**%**
Ain Shams Engineering Journal	1	6%
Alexandria Engineering Journal	2	11%
Automation in Construction	1	6%
Case Studies in Construction Materials	1	6%
Developments in the Built Environment	2	11%
International Journal of Project Management	2	11%
Journal of Building Engineering	4	22%
Journal of Business Research	1	6%
Journal of Cleaner Production	1	6%
Project Leadership and Society	1	6%
Sustainable Production and Consumption	1	6%
Technological Forecasting & Social Change	1	6%
Total	**18**	**100%**

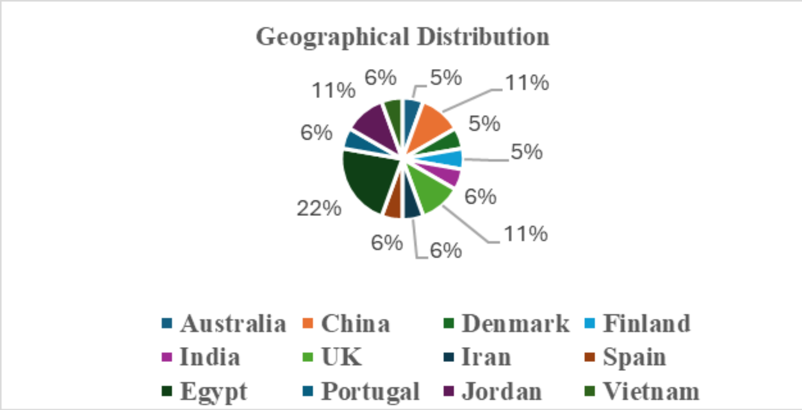

Figure 2: Distribution of articles (annual basis).

Descriptive Analysis

The purpose of this study required examining existing studies according to their primary focus. Since sustainability has three main pillars (social, economic, and environmental), called as the TBL approach, it is of great importance that these pillars are reflected as a holistic approach to construction project management. Therefore, the findings articles were analyzed according to 3 different pillars of sustainability: social pillar focus, economic pillar focus and environmental pillar focus. Most articles focused on TBL as a holistic approach within the construction project management (39%). While some of the studies focused on the combination of the two pillars (social-environmental (11%), economic-environmental (11%)), 33% of the studies in the sample frame focused on the individual pillar as their primary focus. In addition to the primary focus of research, which generally focuses on at least one component of the TBL approach, studies also appear to focus on sustainability reports, building information modeling (BIM), innovation and blockchain technology in construction project management as a secondary focus. (Table 2).

Table 2. Primary focus classification.

Secondary Focus				**Primary Focus**			
Sustainability Reports	**BIM**	**Innovation**	**Blockchain Technology**	**Environmental**	**Social**	**Economic**	**Year**
			x	x	x	x	2023
				x		x	2023
		x				x	2023
				x	x	x	2023
				x	x	x	2023
	x	x		x	x	x	2023
	x	x		x	x	x	2023
				x		x	2023
						x	2023
x				x	x		2023
						x	2021
				x	x	x	2021
	x			x			2021

					x		2021
				x	x	x	2021
	x			x	x		2020
x							2019
						x	2018

Findings

This study aims to examine how sustainability is addressed in the construction project management literature with a holistic TBL approach. In accordance with the purpose, 18 research articles have been evaluated regarding how sustainability is integrated in construction project management. The research articles have evaluated sustainability with different aspects from the perspective of the construction industry. The necessary skills in sustainable construction project management have been analyzed and the issues that form the basis of sustainability have been emphasized (Ershadi & Goodarzi, 2021). Barriers preventing sustainable transition in construction project management have been identified (Fathalizadeh et al., 2021). External barriers to green building policies in the industrial sector and the readiness for adoption of green building practices have been examined (Jaradat et al., 2024). Sustainability stakeholder interaction of the stakeholders involved in the supply chain of construction projects has been discussed (Xue et al., 2020).

Barriers to the adoption of blockchain technology in the sustainable construction industry in India have been identified (Singh et al., 2023). Factors increasing the adoption of innovation for sustainable construction in developing countries have been identified (Van Nguyen, 2023). The level of integration of the sustainable development goal into the decision-making process at the early stage of the construction project has been examined.

Considering the cost of living of sustainable housing projects, the economic benefit of the project living cost has been studied (Salem et al., 2018). In advancing urban sustainability, promoting sustainable change in public institutions and the roles of these institutions in urban sustainability have been examined (Lehtimaki et al., 2023). The implementation and development of sustainability reporting in the construction industry has been examined (Kazemi et al., 2023).

Addressing sustainability in the construction industry, how the circularity of construction waste can be improved, and how targeted strategies for sustainable construction can be implemented to help developing economies have been evaluated (Bao, 2023). Improving the inclusion of construction waste in the circular economy in developing country economies have been studied (Bao, 2023).

Capital barriers to sustainable construction have been examined, and a new three-pillar approach aimed at reducing the entire cost of living has been created, based on a framework related to value management and total quality management (Nasereddin & Price, 2021). A greener and more sustainable building method has been developed through the adoption of modular construction in housing projects in developing countries. (Ali et al., 2023).

The determination of the materials of the buildings designed with BIM modeling has been emphasized and the effects of the determined materials on the sustainability of the buildings throughout their life cycle have been evaluated (Atta et al., 2021). In order to improve the level of sustainability in the construction industry, a comprehensive analysis of life cycle assessment applied to construction materials has been studied (Barbhuiya & Das, 2023). The sustainable level of bridges has been evaluated through a method combining BIM and multi-attribute value function-based methodology (MIVES) (Lozano et al., 2023). A sustainability index for sustainable design, construction, maintenance, and operation processes for highway construction projects have been developed (Ibrahim & Shaker, 2019). The integration of the concept of sustainability into the role of project managers in construction projects has been reviewed (Magano et al., 2021).

Results

This study shows the results of integration process of sustainability into construction project management and intends to offer a perspective of sustainable construction project management. This study aims to show the current state of the art of the sustainability and construction project management in the literature. Additionally, the aim of this study is to raise awareness about sustainable construction management in the construction industry. Therefore, a structured literature search was conducted to find research articles published between 2018 and the first quarter of 2024. The results showed that the majority of studies focused mainly on the environmental and social pillars of sustainability, rather than focusing on TBL as a holistic approach. However, sustainability needs to be evaluated in terms of environmental, social and economic aspects. The majority of studies aimed to identify barriers to the integration of sustainability into construction project management and/or deliver sustainable design and material-based sustainable solutions, rather than creating sustainable project management tools, business models and project delivery systems.

The study focused on the current state of sustainability in construction project management. In this study, it was tried to reach publications between 2018 and the first quarter of 2024 by using Elsevier as a research engine with the keyword combinations of "Sustainability" and "Construction project management", which is a limitation of this study. In future studies, keyword combinations can be increased, and the time period can be expanded.

Since there are limitations of research papers directly focusing on sustainability in construction project management in the literature, the results indicated that there is a lack of published research focusing on TBL as a holistic approach in construction project management. Moreover, sustainable construction project management can be introduced to the construction industry as a new project delivery system in the construction project management literature. This study stresses the importance of integration of sustainability into construction project management. This study, which aims to provide an overview to researchers, will pave the way for sustainable practices in construction project management.

References

Ali, A. H., Kineber, A. F., Elyamany, A., Ibrahim, A. H., & Daoud, A. O. (2023). Modelling the role of modular construction's critical success factors in the overall sustainable success of Egyptian housing projects. *Journal of Building Engineering*, *71*, 106467.

Atta, I., Bakhoum, E. S., & Marzouk, M. M. (2021). Digitizing material passport for sustainable construction projects using BIM. *Journal of Building Engineering*, *43*, 103233.

Bao, Z. (2023). Developing circularity of construction waste for a sustainable built environment in emerging economies: new insights from China. *Developments in the Built Environment*, *13*, 100107.

Barbhuiya, S., & Das, B. B. (2023). Life cycle assessment of construction materials: methodologies, applications and future directions for sustainable decision-making. *Case Studies in Construction Materials*, e02326.

Ershadi, M., & Goodarzi, F. (2021). Core capabilities for achieving sustainable construction project management. *Sustainable Production and Consumption*, *28*, 1396-1410.

Fathalizadeh, A., Hosseini, M. R., Silvius, A. G., Rahimian, A., Martek, I., & Edwards, D. J. (2021). Barriers impeding sustainable project management: a social network analysis of the Iranian construction sector. *Journal of Cleaner Production*, *318*, 128405.

Ibrahim, A. H., & Shaker, M. A. (2019). Sustainability index for highway construction projects. *Alexandria Engineering Journal*, *58*(4), 1399-1411.

Gade, A. N., & Selman, A. D. (2023). Early implementation of the sustainable development goals in construction projects: a Danish case study. *Journal of Building Engineering*, *79*, 107815.

Jaradat, H., Alshboul, O. A. M., Obeidat, I. M., & Zoubi, M. K. (2024). Green building, carbon emission, and environmental sustainability of construction industry in Jordan: awareness, actions and barriers. *Ain Shams Engineering Journal*, *15*(2), 102441.

Kazemi, M. Z., Elamer, A. A., Theodosopoulos, G., & Khatib, S. F. (2023). Reinvigorating research on sustainability reporting in the construction industry: a systematic review and future research agenda. *Journal of Business Research*, *167*, 114145.

Lehtimäki, H., Jokinen, A., & Pitkänen, J. (2023). Project-based practices for promoting a sustainability transition in a city organization and its urban context. *International Journal of Project Management*, *41*(7), 102516.

Lozano, F., Jurado, J. C., Lozano-Galant, J. A., de la Fuente, A., & Turmo, J. (2023). Integration of BIM and value model for sustainability assessment for application in bridge projects. *Automation in Construction*, *152*, 104935.

Magano, J., Silvius, G., de Silva, C. S., & Leite, Â. (2021). The contribution of project management to a more sustainable society: exploring the perception of project managers. *Project Leadership and Society*, *2*, 100020.

Nasereddin, M., & Price, A. (2021). Addressing the capital cost barrier to sustainable construction. *Developments in the Built Environment*, *7*, 100049.

Salem, D., Bakr, A., & El Sayad, Z. (2018). Post-construction stages cost management: sustainable design approach. *Alexandria Engineering Journal*, *57*(4), 3429-3435.

Singh, A. K., Kumar, V. P., Shoaib, M., Adebayo, T. S., & Irfan, M. (2023). A strategic roadmap to overcome blockchain technology barriers for sustainable construction: a deep learning-based dual-stage SEM-ANN approach. *Technological Forecasting and Social Change*, *194*, 122716.

Tuz, A., & Sertyesilisik, B. (2018). An Investigation into the state of the art of the literature on marketing in the construction industry. *Proceedings of 5th international Project and Construction Management Conference,* pp. 629-637, Girne.

Tuz, A., & Sertyesilisik, B. (2020). Finding and minding the gaps in state-of-the-art lean and green marketing in the construction industry. *Market/Trziste*, *32*(2).

Tuz, A., & Sertyesilisik, B. (2021). Integration of the management theories for enhancing green marketing implementation in the construction industry. *A| Z Itu Journal of The Faculty of Architecture*, *18*(3), 653-671.

Tuz, A., & Sertyeşilışık, B. (2023). The preliminary step towards conceptual model for the artificial intelligence-neuro-green marketing in the architectural engineering and construction industry. *Journal of Technology in Architecture, Design and Planning*, *1*(2), 145-155.

Van Nguyen, M. (2023). Drivers of innovation towards sustainable construction: a study in a developing country. *Journal of Building Engineering*, *80*, 107970.

Xue, J., Shen, G. Q., Yang, R. J., Wu, H., Li, X., Lin, X., & Xue, F. (2020). Mapping the knowledge domain of stakeholder perspective studies in construction projects: a bibliometric approach. *International Journal of Project Management*, *38*(6), 313-326.

Yıldız, S., Gültekin, B., & Savural, E. (2018). Kara Harp Okulu laboratuvar merkezi binasinin yeşil bina özellikleri açisindan incelenmesi. *Kara Harp Okulu Bilim Dergisi*, *27*(2), 29-51.

Time Management in the Construction Industry

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Abstract

It is seen that the project process in the construction sector requires a longer and more complex process compared to other sectors. In order for the process to be managed correctly and the activities to progress systematically, the actions and factors of project management must be implemented. The environment in which sectors operate today; it changes regularly under the influence of technological, economic, natural and socio-cultural factors. Changes and developments in the fields of communication and information in recent years, which have developed with technology, have caused competition among companies in the sector and increased the number of business lines in which management and decision-making actions will be carried out. Developing and increasing business lines must be carried out within a limited time. This situation requires managers to pay due attention to time. It seems that effective and efficient use of time is important. In this study, the concept of time management will be emphasized by giving information about project management and its phases in the construction sector. Such a study was needed because it is known that the concept of time is important, especially in construction works in the construction industry.

Keywords: *construction sector, effective time management, project management.*

Introduction

In today's conditions, where everything is accelerated with technological developments and competition is increasing, project managers have to use time effectively, both in quantity and quality, in order to carry out the process in a healthy way and complete the work (Kıral, 2007; Akyüz et al., 2015). Time is a more important factor for a project manager than economic considerations. Managing the concept of time, which is a limiting element, rationally is a necessary condition for success (Şimşek et al., 2007). The value of time is determined by how it is used (Tutar, 2007; Akyüz et al., 2015). Managers who aim to actively run their organization in today's changing conditions must take the concept of time management into consideration in order to achieve their corporate goals. Using time efficiently and effectively should be taken into consideration when managing the process. Since the past, people have had to seek solutions to the complex problems they encounter in life. Developing living conditions and increasing activities with technology have forced us to create different analyses. Nowadays, company problems, which are more complex and comprehensive, create a competitive environment among each other (Coşkun & Ekmekçi, 2012). Project management ensures that projects achieve their goals by planning, programming and controlling the work (Lewis, 2005; Coşkun & Ekmekçi, 2012). Time management, cost and quality concepts are among the main objectives of the projects. In order to manage a successful process in the construction sector, which is complex due to its functioning, it is necessary to take project management phases into consideration (Coşkun & Ekmekçi, 2012). Considering the concept of time, which is one of the most important constraints in the work, ensuring effective time management is of great importance for the successful progress of project management. In this context, the study will first examine project management and its elements, and then the project management process in the construction sector will be discussed. Afterwards, information about the concept of time management, which is the main subject of the study, will be given and the importance of time management in the construction sector will be emphasized. Such a study was needed to emphasize the importance of the concept of time in the construction sector, which is one of the sectors where project management requires the most attention.

Project Management in the Construction Industry

The discipline that has rules about how projects will be carried out is called project management. Project management is a planned approach with the formation of unsuccessful projects. The main purpose of project management is to reach the targeted point and to produce successful projects (Newton, 2006; Kömürlü & Toltar, 2018). According to PMBOK (2013), project management; it is expressed as the application of tools and techniques to meet project requirements and objectives. In other words, project management can be expressed as the coordination of people and activities in line with the project objectives by using the necessary tools with appropriate methods (Barutçugil, 2008). Project management is an active phase in which companies manage their resources in a controlled manner to achieve the goals determined for strategic purposes (Young, 2007; Esatoğlu, 2010). When we look at the information in the literature, in short, project management is defined as all the efforts spent to achieve the goals during the project process. In order to achieve the determined goals, companies need to plan, organize, manage and supervise their resources effectively and efficiently (Kerzner, 1984; Esatoğlu, 2010).

The main element in project management is the project. The management process consists of construction and construction phases. In project management, actions and factors are more important than the final product. Actions and factors are not only related within themselves, but also directly related to building components, building uses and building production (Gültekin, 2007; Parlak Biçer & Karakoyun Yaşar, 2023).

Table 1. Project management actions and factors (PMBOK 2013).

ACTIONS	FACTORS
Planning	Organization
Design	Coordination
Problem solving	Productivity
Decide	Standardization
Monitoring and Control	restrictions
Planning	Economy
	Quality

The actions and factors of project management are listed in the table (Table 1). The actions of project management are interrelated. Some of them can be used more actively depending on the requirements and qualities of the activities. The usage situation may vary depending on the process and the administrator's authority. Generally, project actions are carried out depending on needs and experiments.

Time Management from Project Management Components

Project management components; it consists of subheadings: integration, scope, time, cost, quality, human resources, communication, risk, supply, and stakeholder management. Within the scope of the study, attention was drawn to time management and its importance in the construction industry was mentioned.

Time is a phenomenon that is experienced at every moment but cannot be known exactly (Örücü et al., 2007). It is seen that there is no common definition of the concept of time, which is viewed from different perspectives in different sectors (Yavaş et al., 2012). The need to do a lot of work in a limited time in order to carry out a successful and efficient process in the intense competitive environment of the period, and the need for project managers to be competent in time, revealed the concept of time management (Öncel et al., 2005; Akyüz et al., 2015).

The concept of time management started as an educational tool in Denmark to enable project managers with a large workforce to better organize their time and has spread around the world. In today's conditions, it has become one of the most important elements in being successful in professional business lives (Koch, 1998; Akatay, 2003). The concept of time management according to definitions in different sources; It is to complete the actions that must be carried out within a specified or planned period of time, with a clear beginning and end, by using all resources efficiently for the determined objectives (Ardahan, 2003; Akatay, 2003). According to Smythe and Robertson (1999), time management; It is defined as determining work needs, planning the goals to be fulfilled in order to fulfill these requirements, determining the priority activities to be done, and adapting the time to work by planning in the light of these data (Akatay, 2003).

According to PMBOK (2013), time management activities;

- Planning the timeline,
- Defining and ranking activities,
- Estimating activity sources,
- Developing the schedule by estimating activity durations,
- It consists of processes such as performing time control.

Time Management in the Construction Sector and Its Effect on Project Success

With the development of technology, the variety of products demanded has increased, and it has been observed that management is a necessity in project processes. With project management, it is possible to get quick results, reduce costs, increase quality and ensure profit margin. In order for the project management process to be successful, it is important to determine which techniques will be applied in which projects according to the project conditions. It is necessary to determine that the paths to be followed will differ depending on the project content (Kır, 2007). In project management, general rules, concepts, techniques, studies and tools form the basis of management (Kır, 2007). One of the important conditions for the success of project management is knowing the basic information here. One of the goals of achieving success in projects is the efficient use of time and budget (Er & Kömürlü, 2017).

Problems can be solved by determining a planned method with project management, which is a way to achieve a successful result. To put forward a successful project;

- It is necessary to make sure that the problems are understood.
- It should be developed by creating an action plan to solve the identified problem.
- Someone should be given responsibility to carry out the action plan and solve the problems.
- A date must be determined to solve the problem.
- It is necessary to understand the scope of the project to be implemented.
- It is necessary to determine and implement the intended duration for the activities. Ensuring effective time management affects project success.
- Disruptions can be prevented by ensuring communication management among the stakeholders who will take part in the project. This increases project success.
- Feasibility studies for the project must be carried out at the beginning of the management process. These studies, which reveal the resource and cost requirements of the project, also enable the formation of future project stages.
- Effective management of monitoring and control processes at the end of the project process reveals deviations compared to the plan made at the beginning of the project, plans are reviewed according to the status of deviations and project goals can be successfully achieved (Newton, 2016).

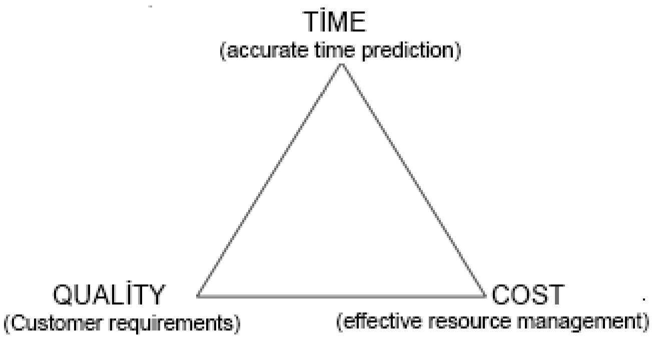

Figure 1: Project success triangle.

To ensure success in project management, time, scope and cost constraints must be planned in line with the determined objectives. Project success is measured by the satisfaction of the project manager and customers (Esatoğlu, 2010). A change in any of the time, cost and quality constraints affects the other. In other words, each of the constraints is related to each other. The results obtained from constraints affect the quality, which reveals the success of the project management process (Kömürlü & Toltar, 2018).

Stakeholders working in the construction sector are open to technological innovations, have a good command of project management techniques related to their field, and are well-equipped, ensuring a successful project in construction works. To manage a successful project process in the construction industry, project size should be taken into account. The order, duration, start and finish dates of the activities to be carried out for the project should be determined and an organizational chart suitable for the work should be created. With the scheme to be created, time delays in the project will decrease, costs will decrease and therefore the project will be successful. Creating project methods according to the scope of the projects is also seen as an important criterion in project success. The project management process must be fully and actively managed. The PMBOK guide states that knowledge domain management consists of different disciplines. When different disciplines come together, the successful implementation and completion of the construction project is achieved thanks to the existence of project management. It has been observed that the content of many projects carried out in the construction sector is quite high. This necessitates taking project management into consideration during the construction process. Resources, cost, time and other constraints must be managed together throughout the entire process from initiation, design and planning, execution, monitoring, control and completion of projects. It is of great importance to take project management principles into account in order for the project to progress successfully from its beginning to its conclusion (Kurşunoğlu, 2017).

Results

The construction sector is of great importance due to its contributions to the world economy. There are complex and long-term studies in the sector. For this reason, the existence of project management becomes important. Project management in the construction industry; planning, organization, decision making, problem solving, etc. It consists of processes. Each process is interrelated. Since each project is unique, project management must also be unique and universal. In this context, the materials, money, equipment and raw materials needed to reach the targeted level within the determined period must be provided.

Nowadays, with the effect of rapidly changing times, the problem of organizations adapting to change comes into play. In order to ensure continuity and success in competitive living conditions, companies must meet conditions such as correct organization, making the right decisions, and quickly making the necessary changes. It is not easy to do a lot of work in a limited time in business lines that are becoming increasingly complex with changing conditions. In other words, the time pressure experienced in the work negatively affects the productivity and performance of project managers. In this context, success in project and time management will be achieved with the managers' ability to manage time. In the construction sector, especially in large-scale project procurements, work must be done according to project management techniques. The importance of project management should be taken into consideration from the beginning to the end of the project. In the planning phase of the project; Time, cost and resource planning is essential. In this way, there will be fewer deviations than expected in the project and a healthy process can be achieved.

The essence of time management is determining personal and work-related requirements and carrying out the work accordingly. The main aim is to increase the quality of the work to be done in a limited time. Time management can be used effectively by taking into account principles such as individual preparation, listing daily goals, determining priority work, completing the specified work at the specified time, making work plans and preventing waste of free time. Time management is seen as a new method strategy where stakeholders can get ahead of their competitors and ensure their continuity. It is important to use capital and time well as a way to differentiate in the competitive environment.

In this study, time management, which is an important stage of project management, is of great importance both in the project management process and in the success of the products obtained. For this reason, in order to produce quality, efficient and successful products, it is necessary to ensure effective use of projects and time management in the construction industry, as in every field, by taking into account the importance of project and time management. The success of the process should be ensured by taking into account the deficiencies in this regard in the audit and control processes.

References

Akatay, A. (2003). Time management in organizations. *Journal of Selçuk University Social Sciences Institute, 1*(10), 281-300.

Akyüz, B., Ünal, Ö. F., Mete, M., & Doger, F. (2015). Time management in the construction industry: a research on Turkish construction sites in northern Iraq. *Süleyman Demirel University Social Sciences Institute Journal, 1*(21), 85-106.

Coşkun, O., & Ekmekçi, İ. (2012). Examining the phases and time and cost analysis of a construction project through project management techniques. *Istanbul Commerce University Journal of Science, 10*(20), 39-53.

Çelik, A., Şimşek, M. Ş., & Soysal, A. (2016). *Time management: effectiveness in managerial time*. Turkish Culture and Tourism Ministry.

Er, A., & Kömürlü, R. (2017). The importance of planning in refinery projects and suggestions for successful planning. *Journal of Architecture and Life, 2*(2), 253-264.

Esatoğlu, N. (2010). *Information technologies project management and success conditions* [Master thesis]. Ankara University Institute of Social Sciences.

Kır, E. (2007). *Project management in the software industry* [Master thesis]. Kadir Has University.

Kömürlü, R., & Toltar, L. (2018). Project management in construction: impact on the success of the project. *Journal of Architecture and Life, 3*(2), 249-258.

Kurşunoğlu, Z. (2017). A research on success criteria in project management [Master thesis]. Gebze Technical University.

Newton, R. (2016). *Project management step by step*. Pearson - Optimist Publishing.

Örücü, E., Tikici, M., & Kanbur, A. (2007). An empirical research on time management in businesses operating in different sectors: the example of Bursa province. *Electronic Journal of Social Sciences, 6*(20), 9-31.

Parlak Biçer, Z. Ö., & Karakoyun Yaşar, E. (2023). Project management and planning action in the construction industry. *Proceedings of 3. International Congress on Construction Materials Engineering and Architecture,* pp. 30-42, Gaziantep.

PMBOK (2013). *Project management knowledge guide* (5th ed.). Project Management Institute.

Yavaş, Ü., Öztürk, G., Açıkel, C. H., & Özer, M. (2012). Evaluation of time management skills of medical school students. *TAF Preventive Medicine Bulletin*, *11*(1), 5-10.

Cost Control of Residential Buildings through Design Management

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Abstract

This study focuses on the challenge of optimizing construction costs in residential projects using strategic design management. This study evaluates the impact of design modifications on project costs and long-term operational expenditures using a simulation approach. The simulation methodology includes two basic steps: first, insulating materials were used to investigate their effects on operating costs, and then modifications were made to the design while incorporating sustainable and environmentally friendly features to evaluate their impact on project and operating costs over time. The study's key findings highlight the significant cost reduction achieved using insulation materials, design modifications, and the use of renewable energy. The research emphasizes the economic benefits over the life of the building and the broader impacts of design decisions on the feasibility, sustainability, and environmental impact of residential projects. Integration of sustainable elements reveals insights into long-term operational cost reductions and environmental benefits. The study concludes that using insulating materials, choosing a thoughtful design, and using renewable energy sources have a significant impact on the cost of energy over the long term. The modifications made in this study resulted in approximately 33% energy savings. The results of this study have significant applications in the residential complex sector and make a significant contribution to residential construction practice. This study showcases how informed design decisions can lead to significant cost savings and environmental benefits.

Keywords: *design management, environmental benefits, insulating materials, operational expenditures, renewable energy, residential complexes.*

Introduction

The construction of housing plays a significant role in the economy of a country, accounting for between 3% and 7% of the gross national product. Due to its lack of innovation and productivity improvement, this sector of the economy has long been criticized (Hayward, 2012). This project discusses the problem of optimizing construction costs in the context of residential projects through strategic design management, including assessing the impact of design modifications on project costs and long-term operating expenses and incorporating sustainable and environmentally friendly features to assess their impact on both the project and long-term operating costs. In the residential construction sector, reasons of choosing the research:

- The importance of the issue of improving construction costs in residential projects
- The need for effective design management
- The impact of design on long-term practical costs
- The economic and environmental importance of residential projects.

The aim of this research is to focus on a single residential building case study, the project examines the cost effects of design changes and long-term sustainability benefits, within an undergraduate study's time and resource constraints. It offers targeted analysis, not covering all sustainable features or detailed construction methods. The objectives of this research will cover the following:

- Evaluate design management's impact on cost efficiency and sustainability in residential construction.
- Assess immediate cost savings from value engineering and long-term benefits of sustainable design.
- Showcase cost reductions and operational savings, guiding future eco-friendly, cost-effective construction.

Literature review

The literature review explores the intersection of value engineering, design management, cost reduction, and sustainability in residential construction projects. This examination provides a comprehensive perspective on these vital themes and emphasizes the need for a delicate balance between economic viability and environmental sustainability.

Value engineering is a methodical process that enhances the value of goods or services by analyzing their functions. Its objective is to attain the required level of quality, reliability, performance, and safety while keeping the cost as low as possible. The primary focus of value engineering is to optimize the value by maximizing the function in proportion to the cost (Rachwan et al., 2016).

Value engineering is a crucial process in the construction industry that helps identify cost-effective alternatives without compromising quality. It promotes innovation and improves efficiency, resulting in reduced costs, time savings, and better quality outcomes. This approach also helps identify design flaws and functional issues, thereby ensuring optimal costs and stakeholder satisfaction. Thus, value engineering leads to superior outcomes in construction projects (John et al., 2020). The use of value engineering in the construction industry has proven to be a highly effective method for both cost reduction and quality enhancement. In addition, it has had a positive influence on green construction practices and environmental impact. (Rachwan et al., 2016) offers a detailed case study highlighting the successful application of value engineering in sustainability disciplines within a large-scale residential project, demonstrating substantial savings in costs and reductions in energy consumption. However, the implementation of value engineering can be challenging due to various factors such as resistance to change, limited understanding or awareness of Value Engineering principles, time constraints, insufficient resources, and difficulty in quantifying intangible benefits (John et al., 2020).

Prior research has employed diverse methodologies to investigate and identify the factors that affect design management, cost optimization, and sustainability in residential construction. Rachwan et al. (2016), Al-Yousefi (2010), Hussein et al. (2021), and John et al. (2020) used case studies and conceptual frameworks, while the integration of building information modeling (BIM) and value engineering is highlighted. For example, John et al. (2020) emphasized the applications of value engineering in housing construction. His study identified areas of high cost and unnecessary expenses and proposed alternative methods for cost reduction. By optimizing elements such as concrete mixes, brickwork, plastering, doors and windows, and painting, significant cost savings were achieved. The study ultimately concluded that value engineering offers cost-effective solutions without sacrificing quality, performance, or reliability. As a result, reductions are achieved by recommending replaceable materials that are locally available. He concluded that using fly ash bricks instead of clay bricks contributed to a 3% reduction in project cost.

On the other hand, both Alalouch et al. (2019) and Ahmed et al. (2019) employed the method of simulation instead of case study. Alalouch et al. (2019) study investigated the potential for energy savings in electricity usage by introducing energy-efficient housing in Oman. This involves analyzing and predicting energy consumption in residential areas, developing simulation models for standard homes in different cities in Oman and other Gulf Cooperation Council (GCC) countries, and conducting economic analyses. The findings show that substantial energy savings (ranging from 13.2% to 48%) can be realized through the implementation of proper building codes. This emphasizes the need for immediate action to promote and enforce energy-efficient housing principles in Oman. Moreover, in his research on the Application of Building Performance Simulation to Design Energy, Ahmed et al. (2019) employed the method of simulation and opinion polling. He used the EnergyPlus program to simulate a residential villa, which helped to reduce the cost by 51.3%. From his findings, he concluded that the orientation of the building and the choice of white paint finish had a considerable impact on reducing the cost of the building. However, the use of LED lights had a minimal effect in reducing the cost of the building, as they only reduced the cost by 2%, 3%, and 2.4%, respectively. On the other hand, the greatest impact on reducing the cost was the use of double glazing, envelope insulation, and selecting an HVAC system with a high coefficient of performance or COP. These measures contributed to reducing the cost by 5%, 20%, and 35%, respectively. Ahmed et al. (2019) concluded that building energy simulation could reduce energy consumption by half. In addition, one of the most significant results of the poll he conducted revealed that almost 80% of specialists do not evaluate the energy performance of their projects. Additionally, two-thirds of them do not do so because clients are not interested in the energy performance of their buildings (Ahmed et al., 2019).

Overall, all researchers concur on the necessity of implementing value engineering in construction, highlighting its crucial role in cost reduction and energy efficiency improvement. Identifying gaps and limitations, the literature reveals a need for further exploration in specific areas. While studies emphasize strategic design management, there is room to delve deeper into the practical implementation of value engineering and sustainable integration. Critical analysis underscores the need to address these gaps and refine methodologies to enhance the robustness of future research.

Methodology

This study uses a simulation approach to assess the impact of design modifications on project costs and long-term operational expenses. The methodology comprises two essential steps: initially using value engineering and optimizing costs by changing the design and materials used in the building to lead to energy cost savings, and subsequently integrating sustainable and environmentally friendly features. For example, using solar panels to generate energy to reduce the cost of electricity in a building. This approach evaluates their influence on both project and operational costs over time in the residential construction sector.

In evaluating these approaches, it is crucial to recognize their strengths and limitations, thus laying the groundwork for methodological considerations in the current project. Through searching for studies similar to this project, a lack of studies using a simulation approach has been noted. Based on this, the simulation method was chosen for this study because it has several strengths, the most prominent of which is the ability to experiment with applying infinite changes in the building design digitally, without the need to spend any budget and much less effort. However, there may be other weaknesses, such as differences between the simulation and actual results.

The study included designing a residential house similar in design to regular houses in the Sultanate of Oman and then making three versions of the same building in addition to the basic design. In the basic design, the cost of building the building and its annual operating cost is identified; however, in the first version, modifications are made to the design. And some materials to try to reduce the cost of building the house only. In the second version, the original version of the building was modified by changing the materials. In the third design, the second design was modified by changing the direction of the building, modifying its design, and adding solar panels to enhance sustainability. Achieving the greatest possible cost reduction over the long term.

Data Analysis and Findings

The cost of the first design was calculated to be US$34,775. This cost covered the expenses for the concrete slab, floor, walls, doors, windows, lights, ceiling, and roof. The second design, which included modifications of materials like insulators, cost US$41,565. The total cost of the third design amounted to US$59,385, which included all the elements of the second design as well as the installation cost of the solar panels. (Table 1 below shows a description of each design).

Table 1. Description of each design.

Element	Design 1	Design 2	Design 3
Orientation	facing south	facing east	facing east
Floor Height	4.6	4.6	4.6
Total Floors	1	1	1
Built Area	155 m^2	155 m^2	155 m^2
Window–Wall (W–W) Ratio	10.5%	10.5%	10.5%
Finish Color	white	white	white

Walls	Wall components: Plaster finishing15 mm, concrete brick 20mm, Plaster finishing15 mm	Wall components: Plaster finishing 15mm, polyurethane insulation 40mm, concrete brick 20mm, polyurethane insulation 40mm, Plaster finishing15 mm	Wall components: Plaster finishing 15mm, polyurethane insulation 40mm, concrete brick 20mm, polyurethane insulation 40mm, Plaster finishing15 mm
Roof	Roof components: Asphalt Bitumen 20mm, Rigid insulation 50mm, Concrete sand/ cement Screed 50mm, cast in concrete 15mm	Roof components: Asphalt Bitumen 20mm, Rigid insulation 50mm, Concrete sand/ cement Screed 50mm, cast in concrete 15mm, polyurethane insulation 40mm, Plaster finishing15 mm	Roof components: Asphalt Bitumen 20mm, Rigid insulation 50mm, Concrete sand/ cement Screed 50mm, cast in concrete 15mm, polyurethane insulation 40mm, Plaster finishing15 mm
Glazing	U-value: 1.0460 W/ (m.k), Single layer glass	U-value: 1.0460 W/ (m.k), Single layer glass	U-value: 1.0460 W/ (m.k), Three-layer glass
Shading	None	None	¼ window height
HVAC	Residential 14 SEER/0.9 AFUE Split/Packaged Gas	Residential 14 SEER/0.9 AFUE Split/Packaged Gas	Residential 14 SEER/0.9 AFUE Split/Packaged Gas
Lighting	Bieger LED Flush Mount 100w, Downlight (7w,10, 18w)	Bieger LED Flush Mount 100w, Downlight (7w,10, 18w)	Bieger LED Flush Mount 100w, Downlight (7w,10, 18w)
Energy Use Index (EUI)	363 kWh/m2/Year	230 kWh/m2/Year	121 kWh/m2/Year

The first design portrays a scenario where a residential house is constructed without any preliminary research or consideration given to future energy expenses. Additionally, no modifications are made to the design or materials used in its construction to enhance its energy efficiency.

This second design presents a scenario where the materials used in a building are replaced with energy-efficient ones to reduce energy consumption over time. This can be a feasible option for the building owner who wishes to cut down on operational costs without making significant changes to the building's form, design, or direction. For instance, if they want to replace non-energy-efficient materials with energy-efficient ones at a later stage of the project design. The design involves adding insulating materials to the walls and roof, such as polyurethane insulation boards, to insulate the building envelope and reduce air conditioning energy consumption.

For the third design, the second design was modified. In this modification, solar panels were added to the roof of the building, which covers 60% of the roof. The design was changed to conduct a study of the sun's movement throughout the year to determine the best direction for the solar panels. The extension of the walls to the roof of the building (roof fence) was eliminated to avoid shadows on the solar panels. A sun visor was added to shade over each window by 1/4 of the length of the window, which helped to reduce direct sunlight from entering. The number of layers of glass was also increased to 3 in the windows to insulate heat as much as possible.

After the third design simulation, it was concluded that the construction cost of the first design was equal to 34,775 US dollars, which had an energy cost of 33.2 USD/m2/Year and 363 kWh/m2/Year, thus consuming 56,265 kWh/Year for the entire building. As for the second design, it cost 41,565 US dollars, which amounted to 17.6 USD/m2/Year and 230 kWh/m2/Year, meaning 35,650 kWh/Year for the entire building. The third building cost 59,385 US dollars, and its energy consumption cost amounted to 2.5 USD/m2/year, at a cost of 387 dollars for the entire building, the results were obtained and presented in the graph below.

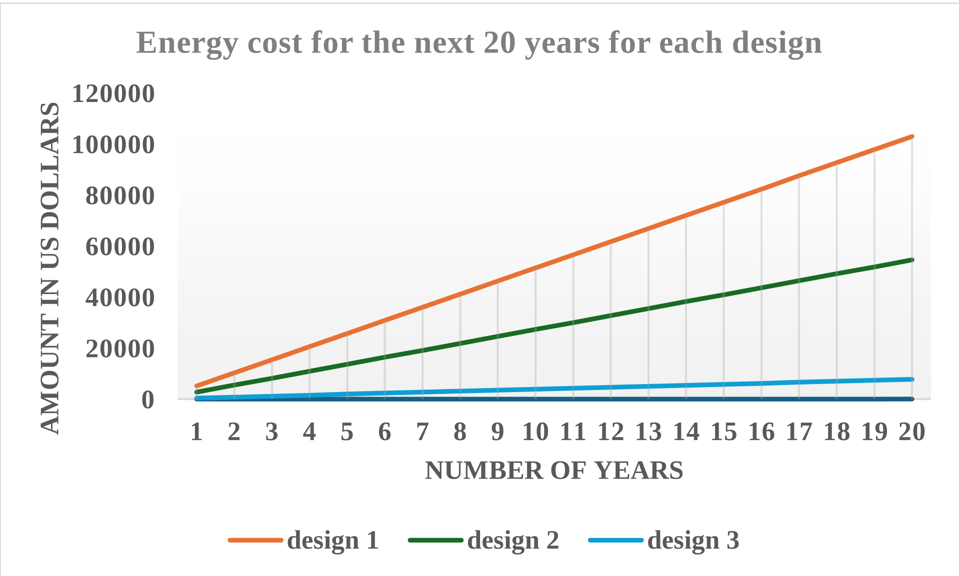

Figure 1: Energy cost for the next 20 years for each design.

The graph displays a 20-year energy cost forecast for the three building designs. Design 1, representing a standard building without energy-saving measures, shows a significant rise in energy costs over time, reaching more than $100,000. Design 2, which includes insulation, suggests a reduction in energy costs compared with Design 1, indicating that insulation contributes to energy savings. However, costs still reach around $60,000 after 20 years, showing that while insulation helps, it does not dramatically curb costs. Design 3 is markedly different; incorporating both insulation and design optimizations for energy efficiency, alongside the integration of solar energy, it demonstrates a remarkably flat cost line. After 20 years, the energy costs for Design 3 remain close to $20,000, highlighting the substantial long-term savings and effectiveness of comprehensive energy-saving measures combined with renewable energy use. This suggests that investing in sustainable design and solar energy can result in significant cost savings over the long term, making Design 3 the most economically and environmentally advantageous option.

Discussion

The obtained results clearly indicate that the cost of constructing the first building is lower than that of the second and third buildings. However, the operational cost of the first building is higher than that of the second building and significantly higher than that of the third building. This suggests that using insulators, making modifications to the design, and using at least one source to generate energy can significantly reduce the operational cost of a building over time. However, there are situations where the first design is more economically attractive, such as when the asset is not intended to be owned for a long period. This period can be determined by simulation. For instance, it may not be feasible to use the third or even the second building design if the asset is to be sold within a period of less than two years. This is because of the high construction cost compared with the difference in energy savings between the two designs. In addition, it is important to consider the ethical and environmental aspects of this issue.

Conclusions

This research on residential construction demonstrates that design management, particularly through optimizing construction costs and sustainable integration, can result in a reduction in the energy costs consumed by the building. Focusing on a single residential building, this study shows that strategic design and materials changes lead to long-term cost savings and operational efficiencies. Key findings demonstrated a marked reduction in energy consumption from 363 kWh/m2/year to 121 kWh/m2/year following the implementation of building modifications and improvements. This translates to a yearly reduction in energy consumption of approximately 33%. Despite the scope limitations of an undergraduate project, the research offers valuable insights for future residential development, advocating for a balance between economic feasibility and environmental sustainability. This study underscores the impact of thoughtful design choices on achieving cost-effectiveness and environmental sustainability in residential construction, contributing to the field’s evolution toward economic viability and ecological responsibility.

To optimize operational energy savings throughout the building’s lifespan, several recommendations are proposed. First, prioritize effective insulation of the building envelope, including ceilings and walls, by incorporating double- or triple-layered glass for windows. Second, consider the building’s orientation, sun movement, and shadow patterns, and implement design adjustments such as sunshades above windows to mitigate solar heat gain. Third, based on previous findings, integrating renewable energy sources is highly beneficial for cost reduction; thus, selecting an appropriate location and design for these sources is essential. Additionally, in hot climates, minimizing window size is advisable to reduce heat infiltration.

By adhering to these recommendations, significant improvements in energy efficiency and cost savings can be achieved in residential construction projects.

To further enhance energy efficiency, it is advisable to use light colors such as white in hot climates. In addition, conducting comprehensive studies before and during the design phase is crucial, given their significant impact on operational and construction costs. Moreover, the selection of HVAC systems should prioritize systems with high coefficients of performance (COP), departing from the common practice of choosing the cheapest option. Engaging expert designers can help address challenges and optimize operational costs. Integration of simulation programs during the design process can identify and mitigate potential gaps before construction begins. Understanding the correlation between the building's intended lifespan and operational costs aids in assessing economic feasibility. It is essential to strike a balance between economic viability, environmental benefits, and impacts. These recommendations, when implemented, can significantly improve the overall sustainability and cost-effectiveness of residential construction projects.

References

Ahmed, W., Asif, M., & Alrashed, F. (2019). Application of building performance simulation to design energy-efficient homes: case study from Saudi Arabia. *Sustainability, 11*(21), 6048.

Alalouch, C., Al-Saadi, S., AlWaer, H., & Al-Khaled, K. (2019). Energy saving potential for residential buildings in hot climates: the case of Oman. *Sustainable Cities and Society, 46*, 101442.

Al-Yousefi, A. S. (2010). *Value engineering application benefits in sustainable construction*. Semantic Scholar.

Hayward, D. (2012). Housing construction industry, competition and regulation. In *International encyclopedia of housing and home* (pp. 395-403). Elsevier.

Hussein, A., Taher, A., Elbeltagi, E., & Abd, I. (2021). *Integration of building information modeling with value engineering analysis to develop sustainable construction projects in Egypt.*

John, F., Reji, A., Vincent, A., & Biju, S. (2020). *Application of value engineering in residential building*.

Rachwan, R., Abotaleb, I., & Elgazouli, M. (2016). The influence of value engineering and sustainability considerations on the project value. *Procedia Environmental Sciences, 34*, 431-438.

Identification of Stakeholder-Based Delay Risks for BOT Infrastructure Projects in the Turkish Construction Industry

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Abstract

The Turkish government has been providing major infrastructure of services for more than three decades by implementing the Build-Operate-Transfer (BOT) scheme to overcome budgetary constraints. On the other hand, timely completion in BOT infrastructure projects ensures investor confidence, economic growth, and public satisfaction. Addressing delays safeguards against penalties and enhances competitiveness. Additionally, the complexity of BOT contracts necessitates risk identification for effective mitigation strategies, reducing financial implications and promoting long-term project viability. Ultimately, determining stakeholder-based delay risks in Turkish BOT infrastructure projects is crucial as it enables effective risk management, promotes investor confidence, ensures economic growth, and enhances the overall success and sustainability of BOT infrastructure projects. Existing studies have also revealed major delays in BOT construction projects are happening due to designers, managers, contractors, and owners of projects in the Turkish Construction Industry. Within this background, this study has an aim of evaluating stakeholder-based delay risks for BOT infrastructure projects in the Turkish Construction Industry by adopting a comprehensive literature review. Findings of the study contributes significantly by facilitating a comprehensive and strategic approach to project management, ultimately contributing to the success, attractiveness to investors, and long-term sustainability of BOT infrastructure projects in the Turkish Construction Industry. Project managers can also benefit from study's findings for proactive risk mitigation planning by addressing potential delays, minimizing their impact on project timelines and costs.

Keywords: *BOT, construction industry, delay risks, infrastructure projects.*

Introduction

The construction projects play an important role in national development. According to Sweis et al. (2007) delay in construction projects is an integral part of construction project life. Assaf and Al-Hejji (2006) defined delay in construction projects as time overrun beyond completion date specified in a contract, or the date that the parties agreed upon for delivery of a project. In addition, Stumpf (2000) defined delay as an act or event that extends the time required to perform the tasks under a contract. Stumpf (2000) commented that different methods for analyzing schedule delay lead to differences of opinion between the owner and the contractor. To the owner, delay means loss of revenue through lack of production facilities and rent-able space or a dependence on present facilities. In some cases, to the contractor, delay means higher overhead costs because of longer work period, higher material costs through inflation, and labor cost increases. (Assaf & Al-Hejji, 2006).

Over the last three decades, Turkish governments have intended to privatize major infrastructure Services, mostly through Build-Operate-Transfer (BOT) scheme to liberalize the economy and overcome budgetary constraints. After a fast and motivated start, the adverse effects of political instability, Successive economic crises, and poor risk management slowed down the early Turkish BOT projects in the 1990s. The 2000s, on the other hand, backed by economic growth, political stability, and heavy use of demand and revenue guarantees, have experienced a boom in the infrastructure privatization and transport sector which has been getting the lion's share within the public investment budget for decades, is no exception to this trend. Because risk management is key for successful BOT project implementation, risk allocation practices play an important role in both the success and failure of the projects. Considering Turkish experience, the construction industry is among the locomotive sectors in Turkey that are growing the revenue (Abolelmagd, et al., 2023). Delays in construction projects leave a negative impact on the private and government sector's development. Project completion on the given timeline is dependent on all stakeholders and their participation in the processes. The Turkish Construction Industry is facing significant issues with the effective prioritization of stakeholder-based delay risks within BOT infrastructure projects (Ozcan, 2016). A lack of systematic approach to finding and assessing the key stakeholders, assessing factors contributing to the delays in the project and developing a prioritization framework can increase the ability of the industry to manage the risks proactively. Therefore, identification of stakeholder-based delay risks for BOT projects in Turkey is crucial for ensuring project success, managing uncertainties, and mitigating potential disruptions. The aim of this process is to comprehensively identify and prioritize delay risks associated with various stakeholders involved in BOT infrastructure projects. The scope involves analyzing the impact of stakeholder actions, decisions, and external factors on project timelines and outcomes. To achieve this, a methodical approach is essential, combining data analysis, stakeholder consultations, and risk assessment techniques.

Significance of Identifying Delay Risks in BOT Infrastructure Projects

Delays could lead to higher costs and financial losses for contractors. Numerous things, including poor decision-making, insufficient site management and supervision, a labor shortage, modifications to the scope of work, and postponed approval and alteration of design papers, can cause delays in construction projects. In construction projects, the analysis of delays is a crucial subject of study. Research efforts are concentrated on enhancing delay analysis techniques and settling disagreements before they arise. Construction projects can suffer from stakeholder delays in making decisions (Vu et al., 2019). Project decision-making can be enhanced by taking into account elements including technical proficiency, leadership, complete documentation, and coordination/communication problems.

Due to the number of parties involved and the corresponding number of interlocking contracts required, BOT projects are indisputably complex. In this type of project, each party has to rely on the performance of its counterpart, and is dependent on the lead-time of each stage of the project, which can be lengthy. Furthermore, there are high associated upfront costs. There are also several complex issues, i.e. government stability, which must be resolved, specifically with respect to developing countries. As a result of large capital outlays and the long timescales required to generate returns for investors, BOT infrastructure projects carry an inherent risk. There is an increased probability of problems arising when it is such long timescales are involved. The relative amount of loss could potentially be huge, given the very large capital outlays required. Therefore, the decision to invest in BOT projects is affected largely by the perception of risk. Detecting delays early is crucial for effective project management. Strategies and tools aid in this process. Using project tracking and reporting features, monitoring KPIs, setting notifications and reminders, and regularly communicating with all parties involved in BOT project.

Methodology

Aligned with the aim of evaluating stakeholder-based delay risks for BOT infrastructure projects in the Turkish Construction Industry, this study adopts conducting comprehensive literature review as the methodology. For the creation of an organized stakeholder identification procedure through stakeholder analysis, a total number of 20 research papers related to the research topic were identified. These papers were then reviewed and a frequency analysis was conducted (Table 1).

Frequency Analysis of Stakeholder-Based Delay Risk Factors for BOT projects

Frequency analysis, also referred to as statistical analysis or frequency distribution analysis, is a technique utilized to comprehend the occurrence pattern of events or phenomena across various scales (Hosking & Wallis, 1997). It is used to predict how often certain values of a variable phenomenon (Moore, 1987). In this study, frequency analysis has been conducted to identify and list the most frequent delay factors throughout the focused studies.

In a typical BOT project, many parties exist such as the host country, public institutions, lenders, insurers, sponsors, consultants (technical, financial, and legal), concessionaires (contractor), subcontractors, suppliers, and users. (Yang et al., 2017). In the BOT approach, a concessionaire builds the project, then typically operates it for 30–40 years to payback the project debt and equity investment, and then transfers it to the public party (government, ministry, public agency) at the end of the concession period. Through this process, several stakeholders are involved, and the nature of BOT projects becomes more complex due to the contractual agreements and the allocation of risks between these stakeholders (Aladağ & Işık, 2020). On the other hand, existing literature on delay classifies delay types as excusable and non-excusable delays. A non-excusable delay is defined as a delay caused by the contractor, or any aspect that is within the sphere of control of the contractor whereas an excusable delay is caused by either of the client/the client's agents, Third parties or incidents beyond the control of the client and the contractor. Taken into account that general delay classification points out two key main stakeholders and BOT models mainly include partnerships involving collaboration between public institution (owner) and a private-sector company (concessionaires/contractor), this study has a limitation of primarily focusing on the two key main stakeholders in BOT models. In this perspective, stakeholder-based delay risk factors were evaluated under four main groups which are public institution (owner) related factors, concessionaires (contractor) related factors, consultant related factors and external factors that are outside of the owner's, contractor's and consultant's control. Table 1 presents frequency analysis of existing literature on stakeholder-based risk factors for BOT projects.

Table 1. Frequency analysis of existing literature on stakeholder-based delay risk factors for BOT projects.

Delay Risk Factor Group	Delay Risk Factors	Study Code																				Freq.
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Public Institution (Owner) Related Factors	Lack of proper feasibility study		✓		✓			✓			✓		✓	✓		✓		✓	✓		✓	10/20
	Unclear goals & Insufficient research on the project			✓			✓			✓	✓			✓								5/20
	Lack of funding & Inconsistent payments		✓									✓	✓		✓		✓		✓			6/20
	Poor coordination and response delay to contractor requests	✓	✓			✓		✓			✓		✓	✓				✓	✓			9/20
	Owner changes to the project		✓							✓					✓	✓	✓					5/20
	Delay hiring suppliers and contractors			✓									✓						✓			3/20
	Decision-Making			✓	✓			✓			✓	✓	✓			✓			✓		✓	9/20
	Frequent suspension of works									✓			✓						✓			3/20
	Owner and/or representatives' lack of project technical competences and leadership							✓		✓	✓						✓				✓	5/20
Concessionaires (Contractor) Related Factors	Continual substitutions of subcontractors									✓					✓		✓					3/20
	Unskilled technical staff and lack of experience			✓		✓				✓	✓	✓	✓	✓		✓		✓	✓			10/20
	Failure to coordinate with project involved parties			✓			✓		✓		✓		✓		✓		✓		✓			8/20
	Poor site management			✓			✓		✓		✓	✓		✓	✓	✓		✓			✓	10/20
	Insufficient resource	✓					✓			✓		✓		✓		✓			✓			7/20
	Poor project timing and planning	✓			✓		✓			✓		✓							✓		✓	7/20
	Technical difficulties & Mistakes that will require rework						✓			✓		✓		✓		✓		✓				6/20
	Failure to timely deliver materials to site	✓				✓						✓		✓				✓				5/20

Table 1. Frequency analysis of existing literature on stakeholder-based delay risk factors for BOT projects (Continued).

Delay Risk Factor Group	Delay Risk Factors	Study Code																				Freq.
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Consultant Related Factors	Mistakes in drawings and BOQ specifications	✓			✓				✓						✓	✓	✓					6/20
	Late delivery of design works and authority approvals				✓								✓						✓			3/20
	Incomplete contract documents				✓				✓						✓		✓					4/20
	Poor coordination with other parties				✓	✓			✓					✓		✓		✓				6/20
	Lack of experience and poor consulting	✓			✓				✓													3/20
	Delays during the government approval process		✓		✓				✓				✓		✓		✓		✓			7/20
	Inadequate building codes		✓		✓				✓		✓		✓	✓	✓		✓	✓	✓			10/20
External Factors	Construction accidents									✓												1/20
	Epidemics and/or worldwide financial crisis, Natural catastrophes						✓											✓				2/20
	Delay in utilities like water, electricity	✓	✓				✓			✓												4/20
	Changes to government policies, rules, and laws		✓								✓		✓		✓		✓		✓			6/20

1-Yaseen, et al. (2020) ; 2-Budayan et al. (2019) ; 3-Budayan, et al. (2020) ; 4-Abdaljader & Günal (2023) ; 5-Zhang et al. (2020) ; 6-Gureun, et al. (2023); 7-Giannitsaros (2020) ; 8-Liuet al. (2020) ; 9-Assaf (2006) ; 10-Kazaz (2022) ;11-Bejjar (2022) ; 12- El-Razek et al. (2008) ;13- Rahman (2014) ; 14-Fathi et al. (2017) ; 15-JaeannathDaripa (2022) ; 16-C1aire E. Broian (2022) ; 17- Shubham (2013) ; 18-Gunduz et al. (2013) 19-Han (2005) ; 20-Kazaz et al. (2012)

Findings

As it can be identified from Table 1, a total number of 28 stakeholder-based delay risk factors for BOT projects were found out under four group. This table essentially quantifies how often specific these factors are identified in the literature regarding stakeholder-based risks in BOT projects, providing a useful guide for stakeholders to understand common challenges in these projects. According to the frequency analysis results:

- **Public Institution (Owner) Related Factors:** "Lack of proper feasibility study" emerges as the most frequently mentioned issue, noted in half of the reviewed studies (10 out of 20). This suggests that rigorous upfront analysis is often neglected, which can lead to significant downstream project delays and complications. Conversely, "frequent suspension of works" and "delay in hiring suppliers and contractors" are among the least mentioned factors, each appearing in only 3 out of 20 studies. This indicates that while these issues do occur, they may not be as pervasive or critically impacting as other factors within this group.
- **Concessionaires (Contractor) Related Factors:** Both "unskilled technical staff & lack of experience" and "poor site management" are identified as significant concerns, each cited in 10 out of 20 studies. These issues highlight critical areas where contractor capabilities and site operations can directly affect project timelines and quality. On the lower end, "continual substitutions of subcontractors" appears as a less cited factor, mentioned in only 3 out of 20 studies, suggesting it might be a less frequent or less critical issue relative to others within this group.
- **Consultant Related Factors:** Within the consultant-related factors, "inadequate building codes" stand out as the most cited issue, appearing in 10 out of 20 studies. This situation points to a systemic issue within the planning and regulatory framework that can adversely affect project execution. On the other hand, "lack of experience and poor consulting" is among the least cited issues, discussed in only 3 studies. This could imply that while consultant expertise is critical, problems in this area are less frequently encountered or reported in the literature.
- **External Factors:** Regarding external factors, "changes to government policies, rules, and laws" is the most commonly cited, noted in 6 out of 20 studies. This finding reflects the significant impact that regulatory environments have on BOT projects. In contrast, "construction accidents" is the least mentioned, only appearing in 1 out of 20 studies.

Discussion of Findings

According to the results of frequency analysis; "Lack of proper feasibility study", "Poor coordination and response delay to contractor requests", "Unskilled technical staff & Lack of experience", "Poor site management" and "Inadequate building codes" are the most mentioned stakeholder-based risk factors for BOT projects in existing literature. For BOT projects in Turkey, effectively managing risks that can lead delays is crucial for the successful completion of infrastructure developments, which often involve large-scale constructions and substantial investments. Based on the finding of the study, importance of these determined delay factors are discussed below from the Turkey perspective:

- **Lack of Proper Feasibility Study:** This is a fundamental stage in any BOT project, involving detailed analysis of economic, technical, legal, and environmental aspects (Salman et al., 2007). In Turkey, where many projects involve complex logistics and significant geographical challenges, skipping rigorous feasibility studies can lead to underestimating costs, overlooking technical difficulties, or misjudging market demand (Zalluhoğlu et al., 2020). This misalignment can result in financial losses and project failures, making it crucial to invest adequate time and resources in comprehensive feasibility studies. This result agreed with the study of (Budayan et al, 2019), whose results showed that the most important risks in projects in Turkey are the lack of a feasibility study, and limited cooperation between stakeholders and workshops.

- **Poor Coordination and Response Delay to Contractor Requests:** Efficient communication and prompt decision-making are essential for maintaining project timelines and budgets (Nguyen et al., 2013). In the Turkish BOT environment, where multiple stakeholders including government entities are often involved, delays in responding to contractor requests can cause significant project delays (Yang et al., 2010). Effective coordination ensures that necessary adjustments, approvals, and problem resolutions are handled swiftly, thereby avoiding cost overruns and scheduling issues.
- **Unskilled Technical Staff & Lack of Experience:** The quality of human resources is critical in BOT projects. Turkey's rapidly developing infrastructure sector demands highly skilled technical staff (Işıklar, 2012). A lack of experienced professionals can lead to poor construction quality, safety issues, and ultimately, project delays and increased costs (Emuze & Mhlwa, 2015). Ensuring that staff are well trained and experienced is vital for meeting the technical requirements of complex projects and for the technology transfer often associated with BOT contracts. The result is consistent with the result of the study of (Zhang et al., 2020) in which lack of labor, preparation, equipment, information flow, management, quantity of materials, and random forest approach are some of the most important reasons for delays.
- **Poor Site Management:** Effective site management encompasses the planning, coordination, and control of a project from inception to completion, aimed at meeting client's requirements in order to produce a functionally and financially viable project (Griffith & Watson, 2004). In Turkey, where many BOT projects are large and can be affected by regional issues such as logistic constraints (Zalluhoğlu et al., 2020) and local regulations (Büyükyoran & Gündes, 2017), poor site management can exacerbate these challenges, leading to inefficiencies and increased costs.
- **Inadequate Building Codes:** Building codes set the standard for the safe design and construction of buildings and infrastructure (Liebing, 2011). In Turkey, where seismic activity is significant and environmental conditions vary drastically across regions, inadequate building codes can lead to unsafe structures that may fail to withstand local conditions. Ensuring that building codes are up to date and rigorously enforced is crucial for the safety and longevity of BOT projects (Uzumeri & Uzumeri, 2003).

Conclusion

For over thirty years, the Turkish government has utilized the BOT model for major infrastructure projects to manage budget limitations. Timely completion of these projects is critical as it boosts investor confidence, drives economic growth, and increases public satisfaction. Managing delays is essential to avoid penalties and improve competitiveness, while the inherent complexities of BOT contracts require careful risk identification and mitigation to minimize financial risks and enhance project sustainability. Therefore, this study aims to assess stakeholder-based delay risks in BOT projects through a comprehensive literature review. A total number of 28 stakeholder-based risk factors for BOT projects were found out under four group and they were presented as a result of frequency analysis. According to the results of frequency analysis; "Lack of proper feasibility study", "Poor coordination and response delay to contractor requests", "Unskilled technical staff & Lack of experience", "Poor site management" and “Inadequate building codes” are the most mentioned stakeholder-based risk factors for BOT projects in existing literature. Addressing these issues requires a focused approach involving better planning, improved training and qualifications for technical staff, more rigorous enforcement of building codes, and enhanced coordination mechanisms among all stakeholders. This strategic focus will help mitigate risks and increase the success rate of BOT projects in Turkey.

References

Abdaljader, A., & Günal, M. (2023). Identification of risks causing delays in design development and construction stages of state-owned irrigation projects in Turkey. *International Journal of Nonlinear Analysis and Applications, 14(1)*, 2341-2349.

Abd El-Razek, M. E., Bassioni, H. A., & Mobarak, A. M. (2008). Causes of delay in building construction projects in Egypt. *Journal of Construction Engineering and Management*, *134*(11), 831-841.

Abdul-Rahman, H., Berawi, M. A., Berawi, A. R., Mohamed, O., Othman, M., & Yahya, I. A. (2006). Delay mitigation in the Malaysian construction industry. *Journal of Construction Engineering and Management*, *132*(2), 125-133.

Abolelmagd, Y., M., Mobarak, W. F., Eskander, R., & F. (2023). Evaluating Delay Causes for Constructing Road Projects in Saudi Arabia *International Journal of Construction Management*, 22(4), 678-689.

Ahmadi-Javid, A., Fateminia, S. H., & Gemünden, H. G. (2019). A method for risk response planning in project portfolio management. *Project Management Journal*, *51*(1), 77-95.

Aladağ, H., & Işik, Z. (2020). The effect of stakeholder-associated risks in mega-engineering projects: A case study of a PPP airport project. *IEEE Transactions on Engineering Management*, 67(1), 174-186.

Alaghbari, W., Razali A. Kadir, M., Salim, A., & Ernawati. (2007). The significant factors causing delay of building construction projects in Malaysia. *Engineering, Construction and Architectural Management*, *14*(2), 192-206.

Arefazar, Y., Nazari, A., Hafezi, M. R., & Maghool, S. A. H. (2022). Prioritizing agile project management strategies as a change management tool in construction projects. *International Journal of Construction Management*, 22(4), 678-689.

Assaf, S. A., & Al-Hejji, S. (2006). Causes of delay in large construction projects. *International Journal of Project Management*, *24*(4), 349-357.

Ali, B., Aibinu, A. A., & Paton-Cole, V. (2022). An investigation of difficulties in information management for delay and disruption claims. *IOP Conference Series: Earth and Environmental Science, 1101*(5), 052023.

Budayan, C. (2019). Evaluation of delay causes for BOT projects based on perceptions of different stakeholders in Turkey. *Journal of Management in Engineering*, *35*(1).

Budayan, C., Okudan, O., & Dikmen, I. (2020). Identification and prioritization of stage-level KPIs for BOT projects – evidence from Turkey. *International Journal of Managing Projects in Business*, *13*(6), 1311-1337.

Büyükyoran, F., & Gündes, S. (2017). The third bosphorus bridge and the northern marmara motorway project. *International Journal of Transport Development and Integration*, *2*(1), 60–70.

Emuze, F., & Mhlwa, C. (2015). Managing Quality on Construction Sites in South Africa: An Eastern Cape Study. *Journal of Construction Project Management and Innovation*, *5*(2), 1224–1237.

Ezeldin, A. S., & El-Hakim, Y. (2022). Analysis of concurrent delays in the construction industry. *Lecture Notes in Civil Engineering*, 25-40.

Fathi, M. S., Daud, M. Y. M., & Baharum, H. I. (2017). Project Practitionersâ€™ Competency in Malaysian Construction Industry. *Sains Humanika*, 9(1-4).

FIEC Turkey. (2020). *Overall construction activity*. Retrieved from https://fiec-statistical-report.eu/2021/turkey.

Giannitsaros, N. (2020). *Factors that affect success of bot projects*. Hermes airports case study (Doctoral dissertation, Business Administration Programm, School of Economic Sciences and Business, Neapolis University Pafos).

Griffith, A., & Watson, P. (2004). Effective and Efficient Site Management. In *Construction Management: Principles and Practice*. 24–85.

Gündüz, M., Nielsen, Y., & Özdemir, M. (2013). Quantification of delay factors using the relative importance index method for construction projects in Turkey. *Journal of Management in Engineering*, *29*(2), 133-139.

Gurgun, A. P., Koc, K., Alçura, G. A., & Gürsoy, M. (2023). PPP state-of-the-Art in Turkey during COVID-19 outbreak: Evidence from a transportation project. *Revisiting Public-Private Partnerships*, 195-209.

Han, S. H., Diekmann, J. E., & Ock, J. H. (2005). Contractor's risk attitudes in the selection of international construction projects. *Journal of Construction Engineering and Management*, *131*(3), 283-292.

Hosking, J. R. M., & Wallis, J. R. (1997). Regional frequency analysis. In *Cambridge University Press eBooks*. 1–13.

Işıklar, A. (2012). Apprenticeship training in Turkey. *Khazar Journal of Humanities and Social Sciences*, *15*(4), 64–73.

Jagannath Daripa, D., Akan, G. T., & Gurdamar, S. (2022). Reasons for delays in public projects in Turkey. *Construction Management and Economics,* 3(2), 171-181.

Kazaz, A., Ulubeyli, S., & Tuncbilekli, N. A. (2012). Causes of delays in construction projects in Turkey. *Journal of civil Engineering and Management*, 18(3), 426-435.

Liu, Y., Gui, Y., Zhou, Y., Ma, Y., Yang, B., Luo, F., Chen, H., Liu, Y., Yan, Z., & Li, L. (2020). A case study on international engineering risk management under BOT model: The case of Yavuz Sultan Selim Bridge in Istanbul. *IOP Conference Series: Earth and Environmental Science*, *568*(1), 012050.

Lokeshwaran M., & Aswin Bharath A. (2023). A Literature Review on Developing Causes and Mitigation Strategies of Delay in Construction Projects: Gaps between Owners and Contractors in Successful and Unsuccessful Projects. *International Journal of Advanced Research in Science, Communication and Technology*, 822–830.

Mathew, A. M., & Lal, N. S. (2021). Identification of risk factors leading to cost and time overrun in B-O-T projects. *Sustainability, Agri, Food and Environmental Research*, *10*(1), 10.
.
Moore, R. J. (1987). Combined regional flood frequency analysis and regression on catchment characteristics by maximum likelihood estimation. *Regional Flood Frequency Analysis*, 119-131.

Ozcan, I. C. (2016). Risk Management in Turkish Transport BOT Projects. *European Transport-Trasporti Europei*, (62).

Nguyen, K. T. P., Marmier, F., & Gourc, D. (2013). A decision-making tool to maximize chances of meeting project commitments. *International Journal of Production Economics*, *142*(2), 214–224.

Rahman, M. M., Lee, Y. D., & Ha, D. K. (2014). Investigating main causes for schedule delay in construction projects in Bangladesh. *Journal of Construction Engineering and Project Management*, *4*(3), 33-46.

Salman, A. F., Skibniewski, M. J., & Basha, I. (2007). BOT viability model for large-scale infrastructure projects. *Journal of Construction Engineering and Management*, *133*(1), 50-63.

Sambasivan, M., & Soon, Y. W. (2007). Causes and effects of delays in Malaysian construction industry, *International Journal of Project Management* 25(5): 517–526.

Shubham, K. (2013). Causes and effects of delays in large construction projects. International *Journal of Research in Engineering and Technology*, 2(2), 368-373.

Sweis, G.; Sweis, R.; Abu Hammad, A.; Shboul, A. 2008. Delays in construction projects: the case of Jordan, *International Journal of Project Management* 26(6): 665–674.

Tarik Kazaz, Gerard, Romme, J., & Van. (2022). Delay Estimation for Ranging and Localization Using Multiband Channel State Information. *IEEE Transactions on Wireless Communications*, 21(4), 2591–2607.

Uzumeri, S. M., & Uzumeri, Y. (2003). A Building Code is of Value Only if it is Enforced. In *Springer eBooks*. 517–526.

Yang, C., Wang, S., & Wang, Y. (2019). Risk identification and assessment for BOT projects: A case study of a highway project in China. *Journal of Construction Engineering and Management*, 145(3), 04018111.

Yang, J. B., Yang, C. C., & Kao, C. K. (2010). Evaluating schedule delay causes for private participating public construction works under the Build-Operate-Transfer model. *International Journal of Project Management*, *28*(6), 569–579.

Yang, J., Nisar, T. M., & Prabhakar, G. P. (2017). Critical success factors for build–operate–transfer (BOT) projects in China. *The Irish Journal of Management*, *36*(3), 147-161.

Yaseen, Z., M., Ali, Z., H., Salih, S., Q., N. (2020). Prediction of risk delay in construction projects using a hybrid artificial intelligence model. *Sustainability*, 12(4), 1514.

Zalluhoğlu, A. E., Aracıoğlu, B., & Erden, G. (2020). Challenges of project logistics in Turkey. *CenRaPS Journal of Social Sciences*, *7*(2), 142–152.

Zhang, YuXiang, et al. (2022). How Does Experience with Delay Shape Managers' Making-Do Decision: Random Forest Approach. *Journal of Management in Engineering*, 36(4), 04020030.

Design and Construction Considerations for Multi-Storey Buildings with Prefabricated Pre-Finished Volumetric Construction (PPVC)

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Abstract

The world population is increasing day by day. With the increasing population, the need for shelter also increases, and construction activities are accelerating to meet the need. Constructions made with traditional methods are responsible for a significant part of the world's energy consumption and environmental pollution. After the industrial revolution in England in the second half of the 18th century, technological developments accelerated, and sustainable industrialized construction systems began to be developed to minimize the damage caused by construction activities to our world and to meet the need for housing with low costs in a short time. The Prefabricated Pre-Finished Volumetric Construction (PPVC) is one of the industrialized and sustainable construction systems, which is recommended and encouraged to be adopted by the construction sector within the scope of the Construction Sector Transformation Map published by the Building and Construction Authority established by the Singapore government. Within the scope of the study, the Prefabricated Pre-Finished Volumetric Construction (PPVC) was evaluated and the points to be considered during its design and construction were specified.

Keywords: *ppvc, prefabricated, prefabricated modular construction systems, prefabricated multi-storey buildings*

Introduction

Technological developments accelerated after the industrial revolution in England in the second half of the 18th century. To accelerate construction activities and reduce costs by taking advantage of developing technology, the construction sector has begun to industrialize, prefabricated construction systems have been developed. In prefabricated construction systems, the building elements produced in the factory are transported to the construction site as disassembled or assembled, and the building elements are assembled within the construction site. Prefabricated structures can be produced using less labor force, in a shorter period and at less cost. Prefabricated construction systems, which were not widely used until the Second

World War, has come to the fore again because the destruction caused by the Second World War caused a major housing problem. The system, which is faster, lower cost and more productive than traditional construction systems, has spread all over the world, especially in Europe and Russia.

Due the increasing population in the world, the need for shelter also increases, and construction activities are accelerating to meet the need. However, construction manufacturing using traditional methods is responsible for a significant portion of the world's energy consumption and environmental pollution. Energy consumption, which starts from the production of materials to be used in the construction process of buildings, continues during the construction, use of the building and demolition of the building. Considering the buildings that are mostly built with traditional construction techniques and building understanding without considering their future, and today's consumption habits, these structures pose a problem for our future. Prefabricated construction systems are environmentally friendly, sustainable, industrialized construction systems in which the use of materials and resources is optimized.

Prefabricated Pre-Finished Volumetric Construction

The Building and Construction Authority (BCA), established by the Singapore's Ministry of National Development, has published the Built Environment Industry Transformation Map (ITM) to popularize sustainable urban systems. Within the context of the urban landscape in Singapore, The Prefabricated Pre-Finished Volumetric Construction (PPVC) system has been defined as a strategic force to enhance construction efficiency. The adopted principle involves optimizing resources throughout the life cycle, spanning planning and design, construction, operation, maintenance, and demolition. This approach aims to transform the built environment into a technologically advanced and highly productive sector. In the current era where the use of prefabrication methods in construction is increasingly prevalent, the PPVC system comes to the fore with the aim of increasing productivity and efficiency. PPVC is defined by BCA as a construction method in which 3D independent modules are completed, including internal coatings, fixtures, fasteners, in a fabrication facility established off-site, and are transported to the construction site for installation and assembled. The primary objective of the PPVC system is to optimize resources and enhance construction efficiency and productivity. The PPVC system construction system adopts the principle of design for production and assembly to significantly speed up the construction process.

In traditional construction systems, most of the structural manufacturing (architectural works, mechanical and electrical installation works) is done on site. In traditional construction methods, which require intensive labor, the continuity and quality of construction depends on many dependent and independent variables, from the design phase to the construction phase, including environmental conditions. In their research Kuru, Erdem and Calis emphasize the most crucial factors affecting construction quality performance, listing them in descending order of significance as follows: In their research Kuru, Erdem and Calis emphasize the most crucial factors affecting construction quality performance, listing them in descending order of significance as follows: "Not considering the project in detail at the beginning", "Inadequate Knowledge or Incomplete Implementation of Quality Standards by Workers ", "Selection of subcontractor company", It states that “Compliance with the contract and its annexes” and “Inter-team cooperation and coordination”. In the Prefabricated Pre-Finished Volumetric Construction (PPVC), all rough and fine structure manufacturing, including volumetric modules, electrical and mechanical installations, walls, wall coverings, floors, floor coverings, ceilings, ceiling coverings and basic furniture, are completed in the factory environment. This allows rapid production without being affected by adverse climatic conditions. It is then brought to the construction site and the modules are installed. The requirement for less labor both on-site and off-site in comparison to traditional systems minimizes errors associated with human factors. This system, with 60% of its components being fabrication, allows for a more precise planning of the construction schedule, enabling a more efficient utilization of time compared to traditional systems. The factors and labor needed for constructing buildings on-site decrease, ensuring that workspaces are secure and conducive to operations.

Benefits of Prefabricated Pre-Finished Volumetric Construction

In the PPVC system, where, unlike traditional construction methods, most of the manufacturing is based on factory production, manufacturing such as excavation, filling and landscaping are carried out on the construction site, while prefabricated modules are produced in parallel. The integrated and simultaneous progression of manufacturing with on-site activities leads to the emergence of new business sectors outside the construction site. These new business sectors contribute to industrial growth and pave the way for economic. The utilization of the PPVC system significantly mitigates on-site construction activities. Due to the increased off-site manufacturing associated with this system, waste generated from on-site construction processes diminishes, thereby reducing environmental and noise pollution. The reduction in on-site construction activities results in decreased labor requirements and diminished hazards for the workforce within the construction site. Conversely, the augmented workforce in the factory environment operates with reduced individual working hours, fostering a safer and improved working environment. The adoption of fabrication techniques contributes to a productivity surge of over 40% in the construction sector, facilitating approximately 20%-time savings. Furthermore, the final product, manufactured in a controlled environment, attains elevated levels of quality.

Key Considerations in Module Design and the Module Production Process for Prefabricated Pre-Finished Volumetric Construction

Contractor Selection: Contractor selection is of paramount importance in the PPVC construction system, as in all construction systems. In traditional construction systems, construction activities are carried out within the construction site, allowing for potential design errors to be identified and addressed on-site. However, in the PPVC system, where a significant portion of manufacturing is based on factory production, there is no possibility of intervening on-site to address potential design errors. Any modifications needed after the completion of module production result in increased costs and time loss. Therefore, the main contractor should be decided at the design stage and given the opportunity to provide input into the project. Design and project planning should be done by expert and experienced personnel in the field, and possible design errors should be prevented with the participation of the contractor who is an expert in the field. This approach enhances the constructability and productivity of the PPVC system.

The Selection of Module Type and Module Dimensions: When designing modules, the primary consideration that should be given priority is the selection of the module type. In the PPVC construction system, the most crucial factors influencing cost and the construction process are the dimensions and, consequently, the weights of the modules. Numerous manufacturing elements, particularly on-site layout and logistics are directly or indirectly affected by this choice. The weights and dimensions of the modules are determined by the material selection in the design and the intended function of the designed structure, within the legally specified limits. The ceiling heights of the modules must meet legal requirements. Modules can be produced in concrete or steel, and the system weight may vary depending on the selected system. Each country and region have legal restrictions set by highways authorities regarding transportation. To ensure the transportation of modules from the factory to the construction site, legal transportation limitations on the roads in the area where the system will be implemented should be thoroughly analyzed, and material selection for the modules should be made within these limitations during the design process. Following the transportation of modules to the construction site, assembly operations are conducted utilizing cranes. The dimensions and quantities of cranes present on-site are determined in accordance with the weights of the modules. Consequently, during the design phase, the weights of the modules should be established with consideration for the lifting capacities of the cranes intended for use in the field.

Module Geometry and the Assembly of Modules: To facilitate the production of modules and reduce module costs, the geometry of modules should be simplified to the greatest extent possible and made suitable for mass production. In a typical residential project, apartments can be planned by creating four standard modules for living spaces, including rooms such as kitchens, bathrooms, bedrooms, and living rooms. Subsequently, modules can be assembled according to the requirements of the apartments, and different functions can be assigned to various modules using demountable partition walls. During the design phase, the life cycle of the building should be considered, considering future activities such as maintenance, replacement, and renovation by users. To prevent the modules from being damaged because of transportation activities, the design of the modules should be made by taking into consideration the temporary situation planned to be transported to the field after production in the factory and the permanent situation after the assembly in the field, and lifting points should be identified. The junction points of the modules should be carefully considered to ensure load-bearing capacity, and connection elements should be designed considering alignments on the floor, walls, and ceilings. Vertical and horizontal module connections play a crucial role in the structural behavior of buildings against factors such as earthquakes and wind loads. Experts should analyze the behavior of the structure against horizontal and vertical loads, and connection elements should be detailed accordingly. Different applications can be preferred at the connection points of the modules. The use of a bolting system is common in steel modules, while on-site joint construction is widely used in concrete modules. Adequate intervention spaces should be left to access connection elements when needed after the completion of the structure. The common areas such as corridors and staircases, where PPVC modules will be connected, should be concurrently designed when creating module designs. The design should take into consideration the isolation details in the horizontal and vertical junctions of the modules.

Mechanical and Electrical Systems of Modules: In the design of electrical and mechanical installations within the PPVC system, rectifying errors poses considerable challenges, and potential revisions substantially escalate construction costs. Electrical and mechanical installations should be considered from the initial stage to the final stage of module design, and the design of relevant systems should be carried out simultaneously with architectural design. To prevent damage to cables and pipes during the assembly and subsequent phases of module integration, protective elements should be considered. Fire regulations must be complied with when selecting materials to be used in relevant manufacturing. Intervention gaps should be created where necessary, considering possible problems that may occur in the systems or periodic maintenance of the systems. The carbon emissions of the building should be reduced by using automation systems in the building.

In the PPVC construction system, modules can be produced in reinforced concrete or steel, depending on the anticipated material selection in the structural design. The fundamental considerations for module production, based on the selected material type, are compared in Table 1 below.

Table 1. Key Considerations in Reinforced Concrete PPVC Module Production and Steel PPVC Module Production.

Module	Reinforced Concrete Module Production	Steel Module Production
Mold Production	The molds should be durable against potential damage during transportation and production, and they should be made of steel material. The most critical respect in mold design is that the molds should be adjustable to accommodate various dimensions and form various combinations.	
Structural Works	Reinforced concrete modules are produced by connecting structural elements such as columns, beams, load-bearing walls, floors. First, iron works of reinforced concrete elements are carried out, as in traditional construction systems. However, unlike traditional systems, columns, beams, floors, floor bars are connected to each other to form a cage. Permanent installation elements are placed inside the cage. After these productions, the cage system should be checked before concrete pouring. After the control, molds are installed, concrete is poured. Once the concrete has set, the molds are removed, the modules are made ready for architectural manufacturing.	Steel modules are formed by assembling the 2-dimensional frame and the 3-dimensional steel shell with connecting elements, and then welding the elements together. In the production of steel modules, first the raw material of the structural steel to be used in the module must be decided, and production templates for the 2D frame and 3D shell related to the design must be prepared.
Architectural Works, Electrical, Mechanical Installations	Considering the work schedule, manufacturing should be carried out by competent masters in their field in a controlled environment. First, the dimensions of the modules should be checked, and then manufacturing should begin. Completed manufacturing must be protected to prevent the modules from being damaged or affected by weather conditions during transportation to the site.	The steel module must be covered with water-resistant plasterboard or similar material, then the modules must be completed by competent craftsmen. Completed manufacturing must be protected to prevent the modules from being damaged or affected by weather conditions during transportation to the site.

Key Considerations During the Transportation of Modules to the Construction Site and During the on-Site Assembly of Modules in Prefabricated Prefinished Volumetric Construction System

Unlike other prefabricated systems, PPVC modules are not suitable for storage on site due to their size. It is recommended that the modules be assembled quickly after they are delivered to the site. Therefore, timing in transportation is very important. The construction area should be analysed well, transportation planning should be made. If there is a suitable storage area for storing modules at the construction site, this area should be planned correctly, the use of cranes should be optimized to minimize the transportation or removal of PPVC modules. In this way, the possibility of damage to the modules is minimized and transportation costs can be reduced.

During the assembly of the modules on the construction site, attention should be paid to horizontal and vertical alignment. Incorrect alignments cause discontinuities in the structural system of the building and pose a life-threatening risk for building users. It also causes faulty horizontal and vertical combinations of electrical and mechanical systems.

Conclusions

The rapid increase in the world population causes the existing qualified building stock to be unable to meet the housing demand of the increasing population. Construction activities are accelerating to meet this demand. Traditional systems are mostly used in construction activities in Turkiye and around the world. The main reason why these systems are preferred is that they have easy access to the workforce due to their high system experience and that the workforce is cheap. However, in traditional construction systems, where all manufacturing is done on the construction site, intensive labor is required, the continuity and quality of construction depends on many variables from the design phase to the construction phase. This situation can make it difficult to follow the work schedule, cause the construction period to take longer than expected, and increase the construction cost.

With the development of technology, environmentally friendly, sustainable industrialized construction systems have been developed to reduce construction costs and accelerate the construction process. The Prefabricated Pre-Finished Volumetric Construction (PPVC), recommended by the Singapore State Building and Construction Authority (BCA) for the dissemination of sustainable urban systems, stands out as an important example of these systems. The basic principle of Prefabricated Pre-Finished Volumetric Construction is to optimize resources throughout the life cycle of the structure, increasing productivity and therefore construction efficiency. In the Prefabricated Pre-Finished Volumetric Construction, all rough and fine structure manufacturing of the modules is completed in the factory environment, without being affected by environmental conditions, and they are brought to the construction site and the modules are assembled. Less labor is required on and off the field compared to traditional construction systems, and human-induced errors can be prevented with the effective use of technology. Intensive use of fabrication not only enables the work schedule to be planned more clearly, but also shortens the construction process. At the same time, it enables the creation of new business lines in the field of industry and thus paves the way for economic development. Carrying out most of the construction off-site largely prevents environmental pollution and noise pollution. The decrease in manufacturing and workforce in the construction site prevents possible occupational accidents from occurring, and prefabricated production facilities provide employees with better working conditions in a safer environment.

Within the scope of the study, the basic issues that need to be taken into consideration in module design, module production, module transportation and module installation to increase productivity and constructability in the PPVC system have been identified and the identified issues are as follows. Early contractor selection and detailed project preparation with the participation of a contractor who is an expert in the field. By thoroughly researching the legal requirements of the region where the structure will be built and the highway transportation limits in the relevant region, determining the dimensions and weights of the modules and accordingly selecting the material from which the modules will be produced. Making the design by considering the temporary situation planned to be moved to the field after production in the factory and the permanent situation after the assembly to be carried out in the field. Designing modules that are as simple as possible and can be integrated with each other to reduce the cost of modules and facilitate and accelerate fabrication. During the design, the horizontal and vertical joints of the modules, ceiling, wall, floor alignments should be considered in detail and the connection elements should be designed accordingly. Carrying out the electrical and mechanical installation works design simultaneously with the architectural design, from the first stage of the module design to the last stage.

Considering the life cycle of the building in the design, leaving appropriate areas for structural and technical interventions. If the module material foreseen in the building design is reinforced concrete, the molds to be produced from steel material should be adjustable to meet different sizes and combinations. After the installation of the iron cage system, the installation of permanent electrical and mechanical installations, checking the manufacturing and dimensions, starting the concrete casting production, carefully dismantling the molds after the concrete has set. If the module material envisaged in the building design is steel, firstly deciding on the structural steel to be used and supplying the material. Drawing three-dimensional and two-dimensional projects in detail and preparing production templates. After assembling the structural elements together, welding operations are carried out with a welding robot and welding production is checked in detail. Installation of permanent installation elements after checking the completed manufacturing. Covering steel modules with water-resistant plasterboard and similar material. With the completion of structural manufacturing, firstly checking the dimensions of the modules, then starting the architectural, mechanical, electrical installation manufacturing. Controlling the completed manufacturing to prevent the modules from being damaged and affected by weather conditions during transportation to the field. Analyzing whether the construction site is suitable for module storage and optimizing the use of cranes by making the transportation plan, accordingly, reducing the cost of the crane and minimizing the possibility of damage to the modules during transportation or removal. During the construction of the modules, attention should be paid to horizontal and vertical alignments at every stage, thus ensuring the continuity of the carrier system. Pay attention to the junction points of electrical and mechanical systems.

By disseminating the Prefabricated Pre-Finished Volumetric Construction (PPVC) in the construction industry, the productivity and efficiency of the construction industry will increase, and the damage caused by the sector to the environment can be minimized. At the same time, the construction sector will be able to respond to the housing needs of the population more quickly, at less cost, with more qualified and high-quality housing areas.

References

Acar, M.Ş. 2006. History of Concrete Prefabrication in Turkey. *Turkish Prefabricated Association*, 216p.

Design for Manufacturing and Assembly (DfMA). https://www1.bca.gov.sg/ (Access Date: 02.10.2022).

Erturan, B. & Eren, Ö. (2012). Evaluation of the approach to improving building effectiveness and efficiency with modular construction technique. *Engineering Sciences*, 7 (4).

Essiz, Ö., & Koman, İ. (2007). Current Applications with Modular Cell Systems. *Building Magazine*.

Gunawardena, T., Ngo, T., Mendis, P., Aye, L. & Crawford, R. (2018). Time-effective post-disaster housing reconstruction with prefabricated modular structures. *Open houses international*, 39(3).

Gunawardena, T. & Mendis, P. (2022). Prefabricated building systems—design and construction. *Encyclopedia*, 2, 70-95.

Ilerisoy, Z. Y. & Çolak B. B. (2016). Use of modular cell construction system in architectural design. *International architecture and design conference proceedings*, 933-944, (In Turkish).

Lee, J., Park, M., Lee, H. S. & Hyun, H. (2019). Classification of modular building construction projects based on schedule-driven approach. *Journal of Construction Engineering and Management*, 145(5).

Liew, J.Y.R., Chua, Y.S. & Dai, Z. (2019). Steel concrete composite systems for modular construction of high-rise buildings. Structures, 21 (1), 135-149. 16.

Pan, W., Yang, Y. & Yang, L. (2018). High-Rise Modular Building: Ten-Year Journey and Future Development, *Construction Research Congress*, 523-32.

Özdamar Seitablaiev, M. & Umarogullari, F. (2020). Reinforced Concrete Prefabrication in the World and in Turkey. *Journal of Architectural Sciences and Applications*, 5 (2), 309-320.

Prefabricated Prefinished Volumetric Construction (PPVC) Information Kit. https://www1.bca.gov.sg/ (Access Date: 02.10.2022).

Roberts, P. & Sykes, H. Urban regeneration a handbook. https://www.academia.edu/44413799/Urban_Regeneration (Access Date: 02.12.2022).

Tokgöz, H. & Koçak, Y. (2008). The Role of modular coordination in industrialized building design. *Polytechnic Journal*, 11 (3), 275-284.

Utkutug, G. The interaction between the systems that make up the building and the importance of teamwork, architect, and plumbing engineer collaboration. *IV. National Plumbing Engineering Congress and Exhibition*, Izmir.

Time Management Behaviors of Architects

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Abstract

Time is an important resource, and its importance is rising day by day. Architectural design process is complicated, and the realization of the projects within the desired time and quality are possible with the effective time management. Hence, realization of the projects successfully will be possible if time is managed effectively. In the frame of this paper, firstly time and time management in architectural offices and time management variables, namely time planning, time use, time saving, time traps and communication, defined. Time management behaviors of architects were examined firstly within the framework of personal characteristics of architects, secondly organizational differences of the offices. Within the scope of the research, a survey was conducted between the employee and employer architects to measure time management behaviors, and the results obtained were evaluated. In this context, firstly demographic characteristics of the architects and then their relationships with time management variables analyzed. The results of the research showed that not only both employer and employee architects with different experiences aware of the importance of time management for successfully completing the projects, but also number of employees and working years of the offices have an impact on time management behaviors.

Keywords: *architect, architectural design, architectural office, time, time management*.

Introduction

Time is an important resource, and its importance is increasing day by day, since it cannot be put back, stored, and bought. For this reason, using time effectively is of great importance both in private and in business life. Therefore, it has become more important to use time effectively in architectural design offices, where construction project process begins. There is a project-based production of services in architectural design offices. The organization has a subjective structure, which is reconstructed for each project. The realization of the projects at the desired time and quality will be ensured by the effective use of time. Zampetakis et al. (2010) revealed in their studies that individuals' creativity is significantly related to time management behaviors and that time management behaviors may be necessary for the effective use of creative thoughts. Therefore, architectural offices need a good time planning for the successful completion of work. In this research, it was aimed to emphasize the importance of time management in architectural offices and reveal time management behaviors of architects.

Time Management in Architectural Design Offices

Architectural offices, where architectural services are produced, play an important role in the construction industry, since they take part in various phases of the building production process and provide coordinated work with other fields of expertise (Erbil & Akıncıtürk, 2010). The success of architectural offices depends on how well the people working in the office manage time. To achieve goals and get ahead of competitors, it is necessary to maximize both organizational and personal time management skills (Elmezaini, 2015). On the other hand, time management is also an important tool for organizational management (Safonov et al., 2017; Farrell, 2017). The maximum benefit should be obtained by managing time effectively (Akyüz et al., 2015). It is important to use time resources in all kinds of activities for the continuity of architectural offices and completing the projects successfully. Based on the study conducted by Akdemir and Inal (2022), which evaluates time management and employee performance during the pandemic process, within the framework of architecture offices, and evaluating time management approaches such as how to plan time, determine the priorities of organizations, and manage external elements has a positive impact on the performance of the architectural design offices. By managing time effectively and efficiently, it will be possible to achieve the goals of the organization within the complicated structure of architectural offices. It is possible to achieve both personal and organizational success by considering all these time management variables.

In this study, where the time management behaviors of architects were examined, time management was evaluated in terms of five sub-dimensions. These variables are time planning, time use, time saving, time traps and communication. Time planning is one of the important elements in managing time and means determining how much time will be allocated to the tasks to be done and the priority of the tasks. One of the most important problems of many people regarding time management is that they give priority to tasks that are not of primary importance (Eroğlu & Bayrak, 1994). Time use refers to the measurement of people's behaviors and attitudes towards achieving what needs to be done while being aware of the effective use of time and in this way, time loss that may occur within the organization will be prevented and a productive working environment will be provided (Erdem & Kaya, 1998). Time saving refers to the measurement of people's behaviors and attitudes regarding saving time in line with the opportunities offered by the organization (such as working environment, technology, insufficient personnel, tense environment) and getting lost in unnecessary details wastes time that should be devoted to important tasks (Öztürk & Yıldırım, 2018). Time traps are defined as obstacles to using time effectively (Güçlü, 2001) and it is important for people who want to have effective time management skills to be aware of time traps (Bayramlı, 2017). Communication refers to the measurement of people's behaviors and attitudes towards the effect of effective use of communication tools and effective communication between people on time management and expressing the situations to be conveyed in a clear and simple language, it will ensure both time efficiency within the organization and the establishment of healthy relationships between people (Yılmaz & Aslan, 2002).

Research Method

The research focused on measuring time management behaviours of architects working in architectural design offices. A survey technique was used to reveal the behaviours of architects working in design offices. A questionnaire was designed to solicit information about the time management behaviours of architects. A 5-point Likert Scale was used in the survey and 174 architects replied to the question paper. The unit of analysis for the study was both the employee and employer architects working in architectural design offices. Questionnaire was prepared in Google Form. A cover letter and the questionnaire form were sent via e-mail. The cover letter explained the academic purpose of the research and assured confidentiality. The survey method was used as the research method. Statistical analyses of the data in the study were performed using the IBM Spss 25.0 version.

The questionnaire consists of two basic sets of questions. The first set of questions was designed to provide data related to the characteristics of the architects and the offices they are working. The second set of questions was designed to provide data for measuring time management behaviours of architects. Time management behaviours of architects are divided into five groups which are time planning, time use, time saving, time traps and communication. Time planning, time use, and communication were measured with 6 questions, time saving with 9 and time traps with 7 questions. The respondents were asked to indicate their answers by using a five-point Likert-type scale, where 1 = I strongly agree, 2 = I agree, 3 = undecided, 4 = I do not agree, and 5 = I strongly disagree.

Table 1. Gender, age, education, working experience and positions of the architects.

		Number of architects	%
Gender	Women	115	65.7
	Men	59	33.9
	Total	174	100
Age	22-30	113	64.6
	31-40	34	19.4
	41-50	22	12.6
	51≥	5	2.9
	Total	174	100
Education	Undergraduate	116	66.7
	Graduate	58	33.4
	Total	174	100
Working experience	0-1	34	19.5
	1-3	54	31.0
	3-5	19	10.9
	5-7	12	6.9
	7-10	13	7.5
	10>	42	24.1
	Total	174	100
Position	Employer	42	24.1
	Employee	132	75.9
	Total	174	100

Results

Table 1 provides gender, age, education, working experience and positions of the architects. According to the results the gender proportions of the respondent architects were not distributed equally: 115 (65.7%) were women, whereas 59 (33.9%) were men. The results showed that most of the architects working in architectural design offices are women. Most of the architects working in architectural design offices are between 22 and 30 years old (64.6%), undergraduate (66.7%) and have working experience between 0 and 3 years (50.5%) and working as an employee (75.9%). Table 2 provides number of employees and working years of the offices, where architects replied question paper, are working. According to the results most of the offices architects working have employees between 1 and 5 (39.7%), following 6 and 10 employees (30.5%). Most of the offices where architects working have been established between 1 and 5 years ago (25.1%), following 16 and 20 years ago (17.1), however, those established 6 to 10 years ago (15.4) and those established 11 to 15 years ago (14.3) follow at similar rates.

Table 2. Number of employees and working years of the offices.

		Number of architects	%
Number of employees	1-5	69	39.7
	6-10	53	30.5
	11-15	13	7.4
	16-20	1	0.6
	21-25	9	5.1
	26-30	5	2.9
	31≥	24	13.7
	Total	174	100
Working years	1-5	44	25.1
	6-10	27	15.4
	11-15	25	14.3
	16-20	30	17.1
	21-25	19	10.9
	26-30	12	6.9
	31≥	17	9.8
	Total	174	100

Table 3 provides the relationship between time management factors and working experience of the architects. Based on the results obtained, architects who have 7 years to 10 years working experience had the highest point in time planning (10.38) and communication (8.46), 0 to 1 years of working experience had the highest point in time use (16.29) and time traps (19.26). Architects who have 0 to 1 year working experience are not good at in time saving (20.91), high points means since higher scores have a negative meaning as responses are measured as 1 strongly agree to 5 strongly disagree. According to the results obtained, architects who have 0 to 1 year experience and 7 to 10 years' experience are more successful in time management factors than the other groups.

Table 3. Working experience of the architects and time management.

Time management	Working experience	Number of architects	X
Time planning	0-1	34	8.9412
	1-3	54	9.0370
	3-5	19	8.2105
	5-7	12	8.3333
	7-10	13	10.3846
	10>	42	8.9286
	Total	174	8.9540
Time use	0-1	34	16.2941
	1-3	54	14.7037
	3-5	19	15.0526
	5-7	12	14.5833
	7-10	13	14.6154
	10>	42	14.9762
	Total	174	15.1034
Time saving	0-1	34	20.9118
	1-3	54	19.7778
	3-5	19	19.9474
	5-7	12	19.2500
	7-10	13	19.1538
	10>	42	18.0000
	Total	174	19.5057
Time traps	0-1	34	19.2647
	1-3	54	18.9630
	3-5	19	16.1579
	5-7	12	18.5000
	7-10	13	17.0000
	10>	42	17.9762
	Total	174	18.2989
Communication	0-1	34	8.2941
	1-3	54	7.8889
	3-5	19	8.0526
	5-7	12	7.4167
	7-10	13	8.4615
	10>	42	7.5476
	Total	174	7.9138

Table 4 provides the relationship between time management factors and number of employees of the offices. Based on the results obtained, architects working at architectural design offices which have 26 to 30 employees had the highest point in time planning (9.60), time saving (20.20) and communication (9.20). Architects working in architectural design offices which have 6 to 10 employees had the highest point in time use (15.64), and 11 to 15 in time traps (19.92). According to the results obtained, architects who are working in the offices have employees between 26 to 30 are better in most of the time management factors.

Table 4. Number of employees of the offices and time management of architects.

Time management	Number of employees	Number of architects	X
Time planning	1-5	69	9.2464
	6-10	53	9.3585
	11-15	13	8.3846
	16-20	1	7.0000
	21-25	9	8.3333
	26-30	5	9.6000
	31≥	24	7.7083
	Total	174	8.9540
Time usage	1-5	69	14.9565
	6-10	53	15.6415
	11-15	13	14.6923
	16-20	1	14.0000
	21-25	9	14.2222
	26-30	5	15.0000
	31≥	24	14.9583
	Total	174	15.1034
Time saving	1-5	69	19.7246
	6-10	53	19.5472
	11-15	13	19.3846
	16-20	1	18.0000
	21-25	9	19.8889
	26-30	5	20.2000
	31≥	24	18.6250
	Total	174	19.5057
Time traps	1-5	69	18.1449
	6-10	53	18.7925
	11-15	13	19.9231
	16-20	1	11.0000
	21-25	9	17.1111
	26-30	5	16.2000
	31≥	24	17.9583
	Total	174	18.2989
Communication	1-5	69	7.9275
	6-10	53	7.7925
	11-15	13	7.4615
	16-20	1	7.000
	21-25	9	8.2222
	26-30	5	9.2000
	31≥	24	8.0417
	Total	174	7.9138

Table 5 provides the relationship between time management factors and working years of the offices. Based on the results obtained, architects who are working in architectural design offices established 1 to 5 years ago (9.27), 6 to 10 years ago (9.26) and 11 to 15 years ago (9.24) had the highest points in time planning. Architects who are working in architectural design offices established 6 to 10 years ago had the highest point in time use (16.04) and time saving (20.22). Architects who are working in architectural design offices established 1 to 5 years ago had the highest point in avoiding time traps (19.18) and 26 to 30 years ago in communication (8.41).

Table 5. Working years of the offices and time management of architects.

Time Management	Working Years	Number of Architects	X
Time Planning	1-5	44	9.2727
	6-10	27	9.2593
	11-15	25	9.2400
	16-20	30	8.7333
	21-25	19	8.7895
	26-30	12	7.7500
	31≥	17	8.6471
	Total	174	8.9540
Time Use	1-5	44	15.1364
	6-10	27	16.0370
	11-15	25	15.9600
	16-20	30	15.1667
	21-25	19	13.2632
	26-30	12	14.8333
	31≥	17	14.4118
	Total	174	15.1034
Time Saving	1-5	44	20.0455
	6-10	27	20.2222
	11-15	25	20.0000
	16-20	30	19.7000
	21-25	19	18.5789
	26-30	12	18.7500
	31≥	17	17.4706
	Total	174	19.5057
Time Traps	1-5	44	19.1818
	6-10	27	18.1852
	11-15	25	18.8800
	16-20	30	17.7667
	21-25	19	17.4211
	26-30	12	19.0833
	31≥	17	16.7059
	Total	174	18.2989
Communication	1-5	44	7.9091
	6-10	27	7.9630
	11-15	25	7.7600
	16-20	30	7.6667
	21-25	19	8.0526
	26-30	12	8.4167
	31≥	17	8.0000
	Total	174	7.9138

Conclusion

Within the framework of this research, time management behaviors of architects were evaluated. For this purpose, firstly personal characteristics of architects, and secondly organizational differences of the offices were examined. In this context, the relationship between working experience of the architects and time management variables analyzed, following searching the relationship between working years and number of employees of the offices and time management variables. The results of the research showed that not only both employer and employee architects with different experiences aware of the importance of time management for successfully completing the projects, but also number of employees and working years of the offices have an impact on time management behaviors.

References

Akdemir, A., & İnal, İ. H. (2022). Pandemi sürecindeki zaman yönetimi ve çalışan performansı ilişkisinde işe adanmışlık kavramının aracı rolü. *İşletme Araştırmaları Dergisi, 14*(1), 931-946.

Akyüz, B., Ünal, Ö. F., Mete, M., & Doger, F. (2015). İnşaat sektöründe zaman yönetimi: Irak'ın kuzeyindeki Türk şantiyeleri üzerine bir araştırma. *Journal of Süleyman Demirel University Institute of Social Sciences*, *1*(21), 85-106.

Bayramlı, Ü. Ü. (2017). *Zaman yönetimi*. Seçkin Publishing, Ankara.

Elmezaini, N. (2015). Time management in engineering consulting firms. *Journal of Engineering Research & Technology*, *2*(2), 105-111.

Erbil, Y., & Akincitürk, N. (2010). Mimarlık ofislerinin yenilikçilik sürecinde; kullanıcı ve müşterilerin stratejik rolü üzerine kalitatif bir araştırma deneyimi. *Megaron*, *5*(1), 43-50.

Erdem, R., & Kaya, S. (1998). Zaman yönetimi. *Çağdaş Yerel Yönetimler Dergisi*, *7*(2), 99-120.

Eroğlu, F., & Bayrak, S. (1994). Örgüt faaliyetleri açısından zaman yönetimi. *Atatürk Üniversitesi İktisadi ve İdari Bilimler Dergisi*, *10*(3-4), 255-270.

Farrell, M. (2017). Time management. *Journal of Library Administration, 57*(2), 215-222.

Güçlü, N. (2001). Zaman yönetimi. *Kuram ve Uygulama Eğitim Yönetimi*, *25*(25), 87-106.

Öztürk, H., & Yıldırım, T. D., (2018). *Ofis yönetimi el kitabı*. Seçkin Publishing, Ankara.

Safonov, Y., Maslennikov, Y. & Kashubskyi, A. (2017). Time management and its implementation at production companies. *Baltic Journal of Economic Studies, 3*(1), 82-87.

Yılmaz, A. & Aslan, S. (2002). Örgütsel zaman yönetimi. *C. Ü. İktisadi ve İdari Bilimler Dergisi*, *3*(1), 25-46.

Zampetakis, L. A., Bouranta, N., & Moustakis, V. S. (2010). On the relationship between individual creativity and time management. *Thinking Skills and Creativity, 5*, 23–32.

Resilience Concept and Digital Twin in Disaster Management: A Literature Review

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Abstract

In the context of project management, resilience is a concept used to describe the ability to organize in various situations of uncertainty and sudden change because of unexpected events. As a new and promising concept in project management studies, resilience can be supported by digital technologies. The Digital Twin (DT), one of the digital technologies, is seen as a comprehensive tool that can be used for monitoring, analysis, control, and optimization of a structure throughout its life cycle. DT is the creation of a virtual twin of an object in a computer environment for observation and control purposes. In addition to supporting the life cycle of a building, DT can be used for pre-disaster analysis and post-disaster damage assessment studies in a virtual environment. The application of these studies to the whole city is referred to as a "digital twin city in the literature. However, it is utopia to apply and control this technology in an entire city. For this reason, as a more realistic solution, its application in certain parts of the city is discussed in this study. The application of DT technology in public buildings, which are expected to continue to function uninterruptedly and without hesitation after a disaster, is of critical importance. In this study, a conceptual framework is established through the concepts of disaster management, resilience, and DT. The aim of the study is to define the concept of resilience from a project management perspective and to investigate in detail the incorporation of DT into disaster management efforts to strengthen the resilience of the built environment. It was found that the application of DT technology in specific public buildings would be possible and beneficial.

Keywords: *digital twin, disaster management, project management, resilience.*

Introduction

The use of Industry 4.0 and the emergence of third-generation information and communication systems have increased the efficiency of digital technologies (Grieves, 2014). Digital technologies have the potential to enhance many activities such as in-service knowledge acquisition, storage, knowledge creation, use, sharing, risk mitigation, automated production systems, market intelligence, and service innovation (Tao et al., 2018). The emergence and development of new digital technologies (e.g., digital twin, virtual reality, the internet of things, artificial intelligence) have triggered the formation of new approaches in many sectors. One of these new digital technologies, the Digital Twin (DT), is one of the most promising platforms for project management. DT technology is the representation of data about the physical state of an asset in a virtual environment with instantaneous bidirectional information flow (Grieves, 2014). In other words, it is the simultaneous display of data obtained from the physical changes of a real-world object in a virtual environment.

DT has a wide application potential in representing, predicting, and managing current and future conditions of system architecture, infrastructure, the built environment, or city assets. According to the literature, DT can contribute to project management in areas such as intelligent design, operation, control, maintenance, automatic data collection, conceptual development, dynamic analysis, problem diagnosis, and optimization. Therefore, it is believed that the concept of DT will become more and more important in the development of the construction industry (Pan & Zhang, 2021). Studies on DT, one of the new products of Industry 4.0 technologies, have been increasing in recent years (Bhandal et al., 2022).

The ability of DT to test building performance and automatically detect problems in real-time can improve reliability and efficiency in disaster management (Pan & Zhang, 2021). The mentioned features of DT technology can reduce data acquisition time and improve decisions by providing project managers with additional information to make immediate decisions in disaster management (Lindell et al., 2007). It can also optimize disaster management strategies by providing managers with reliable predictions of the likely outcomes of proposed decisions. However, additional studies are needed for improved disaster management (Ford & Wolf, 2020). In addition, question marks remain regarding its implementation in the whole city. The cost and inexperience of the implementation teams are the main questions. This study evaluates the application of DT technology in important public buildings in the city as a step forward.

Today's public buildings are an important building type with increasingly complex functions and high utilization demands. This makes them vulnerable to various threats that can lead to major incidents (Brucherseifer et al., 2021). The resilience of public buildings, which are critical to maintaining their functions after damage, needs to be increased. In this study, a DT concept and conceptual framework for supporting the resilience of public buildings in the context of disaster management are developed. It is aimed at harmonizing existing studies and accelerating the transition of theoretical findings into practice. The benefits that DT technology can provide to increase the resilience of critically important public buildings in the whole city are examined.

Resilience

Resilience The concept of resilience is the subject of many research fields such as ecology, psychology, economics, national security, etc. (Wied et al., 2019). Resilience has been studied in many different fields, such as psychology, disaster management, natural resources, business, and production management (ISDROC, 2004). In the context of project management, resilience is the ability of a system to absorb and respond to disturbances. It is also a concept that describes the ability to learn from the past and anticipate new threats (Brucherseifer et al., 2021). Resilience is the recovery of full functionality after damage to reliably maintain essential services (Ouyang & Wang, 2015). In the field of disaster management, resilience is the capacity of a threatened system or community to reach an acceptable level of functioning as soon as possible (ISDROC, 2004).

As resilience and disaster management practices are continuously discussed and developed, research is ongoing to identify other resilience characteristics, strategies, capabilities, and related technical prerequisites (Engler, 2019). In parallel with the increasing dependence of societies on reliable resources, efforts to improve protection plans against disaster threats have accelerated. Therefore, resilience research has increased in recent years (Brucherseifer et al., 2021).

Disaster Management

Disaster management is defined as a form of project management. However, despite the relationship between disaster management and project management, the lack of interaction between the two literatures is unexpected (Moe & Pathranarakul, 2006). Apart from a relatively small number of papers focusing on recovery and reconstruction, there is little work on the utilization of project management literature in disaster management. Most of these few studies address various project control issues, including quality, cost, and planning. All activities of disaster management, from forecasting, response, recovery, and reconstruction, can benefit from project management approaches. Resilience can be supported with systemic, participatory, flexible, and context-sensitive approaches to project management in disaster management (Crawford et al., 2013).

Disaster management needs to develop new methods and integrate new tools that explicitly address rare and unpredictable events (Brucherseifer et al., 2021). DT can reduce data acquisition time and improve decisions by providing additional information in the rapid decision-making processes of managers in disaster management (Lindell et al., 2007). DT can optimize disaster management strategies by providing managers with reliable estimates of the likely impacts of proposed decisions.

The Concept and Definition of a Digital Twin

DT technology is used in various fields such as smart cities, construction, healthcare, agriculture, cargo transportation, drilling platforms, automobiles, aviation, electricity, etc. The different applications in these areas have led to many DT definitions. The reason for the differences in definitions is related to each author's perspective on the concept of DT. Today's DT definitions vary according to the authors and their purposes (Bécue et al., 2020).

DT is a functional system of process optimization created by the collaboration of physical and digital production lines (Vachálek et al., 2017). It is a simulation of production lines capable of real-time control and optimization (Zhang et al., 2017). It is a method or tool for modeling the behavior and state of entities (Bao et al., 2019). It is an exact representation of a real-world object (such as a machine, component, or part of the environment) or a real subject (a person, software, or system) (Schluse et al., 2017). It is the digital equivalent of a physical object (Kritzinger et al., 2018). It is an integrated system used to simulate, monitor, compute, organize, and control a process (Zheng et al., 2020). It is a virtual representation of a production system whose real-time data obtained through connected smart devices can be synchronized with the production system (Negri et al., 2017).

However, the concept of DT is not new, despite all these differences in definition. It was first established and developed by NASA in the 1960s for the Apollo 13 space program. DT technology allowed NASA to simulate and measure the states of the Apollo 13 spacecraft while in space (Miskinis, 2019). Although the first use of DT goes back a long way, the last decade has seen an increase in DT work across multiple domains. This is mainly since it has only recently reached the maturity of being applied alongside other digital technologies such as the Internet of Things (IoT) (Bhandal et al., 2022).

Digital Twin Potential

As a result of advances in digitalization, the application of DT to large-scale systems is increasing (Brucherseifer et al., 2021). With increasing digitalization, DT can be a kind of next-generation industrial simulation (Boschert & Rosen, 2016). DT can play a role in the product lifecycle for design, manufacturing, operation, and maintenance by collecting relevant data for model-based simulation (Malakuti et al., 2020). It can be applied as a comprehensive tool that can be used to monitor, analyze, control, and optimize a system throughout its entire life cycle (Liu et al., 2021). DT has the advantages of intelligent design, operation, control, maintenance, automatic data collection, conceptual development, dynamic analysis, problem diagnosis, and optimization (Pan & Zhang, 2021).

The disaster context is a special scenario where the process evolves rapidly and becomes complex. In disaster management, DT technology can provide multiple benefits for improved situation assessment, decision-making, coordination, and resource allocation. Combining, learning, and sharing information through data integration, visualization, and virtual coordination can provide a vision for disaster response and emergency management (Fan et al., 2021). DT can provide disaster monitoring and propagation forecasting services for disaster management systems to support the efficient operation of systems (Boschert & Rosen, 2016). DT technology can be applied by organizing it according to the principles of disaster management (Figure 1).

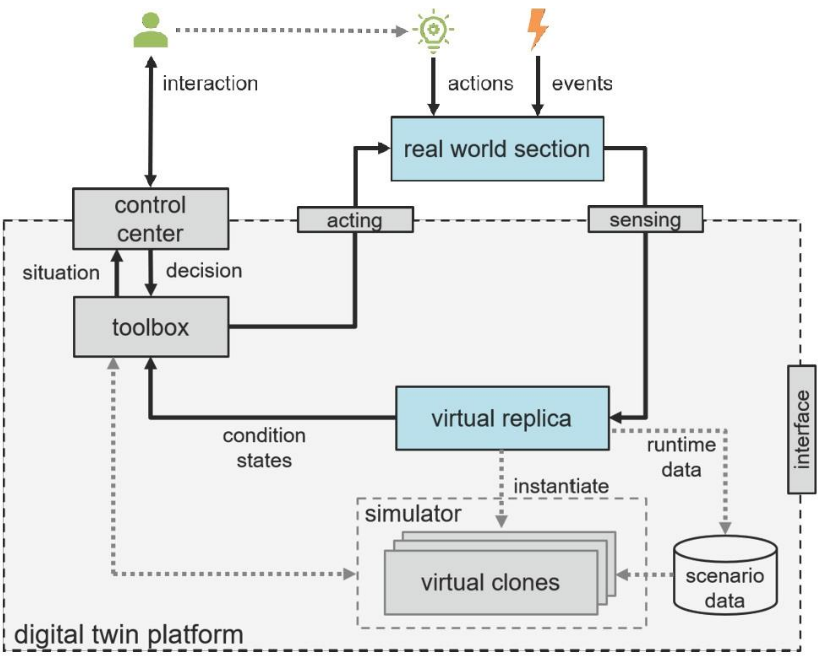

Figure 1: Disaster management and the Digital Twin (Brucherseifer et al., 2021).

Advances in technology allow large amounts of information to be integrated into virtual and physical products. However, feedback and feed-forward information loops from physical to virtual products and vice versa cannot yet be implemented smoothly. For DT to reach the expected level, the simultaneous interaction between physical and virtual products must be fully realized (Ozturk, 2021).

Results

With reference to the results of previous studies, the conceptual framework of the study was established through the concepts of disaster management, resilience, and DT. Recommendations and forecasts for increasing resilience in disaster management are analyzed. The use of current digital technologies in disaster management is seen as a promising development. It is expected that developments in digital technologies will continue, and these developments will be adapted to meet current needs. DT, one of the new digital technologies, is increasing its popularity day by day thanks to its advantages.

In this study, the use of DT technology within the framework of disaster management is proposed. There are many studies on DT cities in the literature. In the future, all cities can be transformed into DT cities. However, in today's conditions, this idea is only a utopia. It is very difficult to turn the whole city into a virtual model and control it instantly through sensors. Cost and the lack of experience of the personnel are the main challenges in implementing DT in an entire city. However, this ideal can be achieved in the future by starting with specific parts of the city. Considering the difficulties in implementing DT in the whole city, it was found that it is possible to implement DT technology at least in critical public buildings after a disaster. The application of DT in public buildings such as hospitals, which are expected to continue to function after a disaster, can increase resilience against disasters. Despite its challenges, DT is a promising approach for disaster management. The application of DT technology in public buildings can contribute to daily use as well as disaster management. It can facilitate disaster management efforts for stakeholders, personnel, and relief forces. Another advantage of DT technology is the recording of data. By enabling retrospective analysis of negligence and risks, weaknesses in structures can be identified. The application of DT technology in public buildings can enable learning from mistakes and developing new approaches.

References

Bao, J., Guo, D., Li, J., & Zhang, J. (2019). The modelling and operations for the digital twin in the context of manufacturing. *Enterprise Information Systems*, *13*(4), 534-556.

Bécue, A., Maia, E., Feeken, L., Borchers, P., & Praça, I. (2020). A new concept of digital twin supporting optimization and resilience of factories of the future. *Applied Sciences*, *10*(13), 4482.

Bhandal, R., Meriton, R., Kavanagh, R. E., & Brown, A. (2022). The application of digital twin technology in operations and supply chain management: A bibliometric review. *Supply Chain Management: An International Journal*, *27*(2), 182-206.

Boschert, S., & Rosen, R. (2016). Digital twin—the simulation aspect. *Mechatronic futures: Challenges and solutions for mechatronic systems and their designers,* 59-74.

Brucherseifer, E., Winter, H., Mentges, A., Mühlhäuser, M., & Hellmann, M. (2021). Digital Twin conceptual framework for improving critical infrastructure resilience. *at-Automatisierungstechnik, 69*(12), 1062-1080.

Crawford, L., Langston, C., & Bajracharya, B. (2013). Participatory project management for improved disaster resilience. *International Journal of Disaster Resilience in the Built Environment, 4*(3), 317-333.

Engler, E., Baldauf, M., Banyś, P., Heymann, F., Gucma, M., & Sill Torres, F. (2019). Situation assessment—an essential functionality for resilient navigation systems. *Journal of Marine Science and Engineering, 8*(1), 17.

Fan, C., Zhang, C., Yahja, A., & Mostafavi, A. (2021). Disaster city digital twin: A vision for integrating artificial and human intelligence for disaster management. *International Journal of Information Management, 56*, 102049.

Ford, D. N., & Wolf, C. M. (2020). Smart cities with digital twin systems for disaster management. *Journal of Management in Engineering, 36*(4), 04020027.

Grieves, M. (2014). Digital twin: Manufacturing excellence through virtual factory replication. *White paper, 1*.

International Strategy for Disaster Reduction Online Conference (ISDROC). (n.d.). *Terminology*. http://www.unisdr.org/2004/wcdr-dialogue/terminology.htm

Kritzinger, W., Karner, M., Traar, G., Henjes, J., & Sihn, W. (2018). Digital twin in manufacturing: A categorical literature review and classification. *IFAC-PapersOnline, 51*(11), 1016-1022.

Lindell, M. K., Prater, C. S., & Peacock, W. G. (2007). Organizational communication and decision making for hurricane emergencies. *Natural Hazards Review, 8*(3), 50-60.

Liu, M., Fang, S., Dong, H., & Xu, C. (2021). Review of digital twin about concepts, technologies, and industrial applications. *Journal of Manufacturing Systems, 58,* 346-361.

Malakuti, S., van Schalkwyk, P., Boss, B., Sastry, C. R., Runkana, V., Lin, S. W., ... & Nath, S. V. Digital twins for industrial applications 2020. https://www. iiconsortium. org/pdf/IIC_Digital_ Twins_Industrial_Apps_White_Paper_2020-02-18. pdf (accessed 15.04. 2024).

Miskinis, C. (2019, December 14). *The history and creation of the digital twin concept, Challenge Advisory.* www.challenge.org/insights/digital-twin-history/

Moe, T. L., & Pathranarakul, P. (2006). An integrated approach to natural disaster management: Public project management and its critical success factors. *Disaster Prevention and Management: An International Journal, 15*(3), 396-413.

Negri, E., Fumagalli, L., & Macchi, M. (2017). A review of the roles of digital twin in CPS-based production systems. *Procedia Manufacturing, 11*, 939-948.

Ouyang, M., & Wang, Z. (2015). Resilience assessment of interdependent infrastructure systems: With a focus on joint restoration modeling and analysis. *Reliability Engineering & System Safety, 141*, 74-82.

Ozturk, G. B. (2021). Digital twin research in the AECO-FM industry. *Journal of Building Engineering, 40,* 102730.

Pan, Y., & Zhang, L. (2021). A BIM-data mining integrated digital twin framework for advanced project management. *Automation in Construction, 124,* 103564.

Schluse, M., Atorf, L., & Rossmann, J. (2017). Experimentable digital twins for model-based systems engineering and simulation-based development. In *2017 Annual IEEE International Systems Conference (SYSCON)* (pp. 1-8), IEEE, Montreal, QC, Canada, 24–27 April.

Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H., & Sui, F. (2018). Digital twin-driven product design, manufacturing and service with big data. *The International Journal of Advanced Manufacturing Technology, 94*, 3563-3576.

Vachálek, J., Bartalský, L., Rovný, O., Šišmišová, D., Morháč, M., & Lokšík, M. (2017). The digital twin of an industrial production line within the industry 4.0 concept. In *2017 21st International Conference on Process Control (PC)* (pp. 258-262), IEEE, Strbske Pleso, Slovakia, 6–9 June.

Wied, M., Oehmen, J., & Welo, T. (2020). Conceptualizing resilience in engineering systems: An analysis of the literature. *Systems Engineering, 23*(1), 3-13.

Zhang, H., Liu, Q., Chen, X., Zhang, D., & Leng, J. (2017). A digital twin-based approach for designing and multi-objective optimization of hollow glass production line. *IEEE Access, 5,* 26901-26911.

Zheng, P., Xu, X., & Chen, C. H. (2020). A data-driven cyber-physical approach for personalised smart, connected product co-development in a cloud-based environment. *Journal of Intelligent Manufacturing, 31*(1), 3-18.

Supplier Selection in the Construction Industry with Fuzzy TOPSIS Method

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Abstract

Supplier selection is a decision-making problem that aims to choose the most suitable one among multiple alternatives. The aim of this study is to use the integrated solution of the TOPSIS method, which is one of the MCDM methods, with the concept of fuzzy logic in the selection of the ready-mixed concrete supplier required for the rough construction production of a construction company. The fact that the method is practical, easy to understand, and the use of quantitative and qualitative values were effective in the preference of the fuzzy TOPSIS method. The data used in the application of the methods are collected at the end of the interviews with three decision makers within the company. First of all, decision makers were asked to determine 6 alternative companies from which they can supply ready-mixed concrete and the criteria that affect their decision making. In the next step, the decision makers were asked to evaluate the importance of the criteria and the degrees of alternatives according to the criteria with verbal expressions. Then, using the fuzzy number equivalents of linguistic evaluations, the mathematical processing steps of Fuzzy TOPSIS and its method were applied and the best alternative ranking was obtained. In the solution, the second company is found to be the best alternative among the alternative concrete companies. This study suggests systematic approaches to construction project managers that support common sense in the supplier selection problem.

Keywords: *construction, project management, fuzzy TOPSIS, multi-criteria decision, supplier selection.*

Introduction

Supplier selection is defined as firms selecting the most suitable alternative supplier in line with their objectives (Dagdeviren & Eraslan, 2008). In order for companies to compete against market conditions and sustain their existence, they need to conduct the supplier selection process in a planned manner (Supciller & Deligoz, 2018). Indeed, choosing the right supplier will reduce business costs, increase customer satisfaction, and ensure reaching the final product in the shortest time with the highest quality (Celik & Cagil, 2021). In the construction sector, selecting the supplier correctly is necessary for the targeted project to be completed within the intended time, cost, and quality (Polat et al., 2017). In the construction sector, a significant portion of the total construction cost is made up of material costs. Therefore, businesses need to prioritize material supply issues to ensure that projects are not delayed, the financial situation is managed correctly, and national wealth losses are prevented (Ugur, 2007).

In construction companies and other businesses, the criteria considered in supplier selection vary. The criteria that construction companies prioritize in supplier selection are: quality, price, delivery terms, technical competence, etc. (Gokalp and Soylu, 2010). Supplier selection is a multi-variable decision-making process that involves many criteria such as price, quality, and lead time, and needs to be solved through scientific and systematic methods. Therefore, instead of leaving supplier selection to individual experiences, it needs to be solved through scientific and systematic methods. The application of Multi-Criteria Decision Making (MCDM) methods in supplier selection can ensure reaching the closest correct solution to the problem. One of the MCMD methods can be used alone, or several of these methods can also be used integratively (Cakin & Ozdemir, 2013).

The aim of this research is to explain the CPM methods that construction companies can use in material supplier selection problems and to provide an example application. In the first part of the study, introductory information about the study was provided and the purpose was explained. Following that, existing studies in the literature were reviewed, and the supplier selection process and criteria were explained; fuzzy logic-based supplier selection methods: fuzzy TOPSIS method was examined. Finally, an example application was made for the selection problem of a ready-mix concrete company to be sourced by a construction company in Istanbul province. The necessary data for solving the problem was collected through interviews with authorized individuals. The findings and results obtained in the final section were evaluated. The purpose of addressing the subject of this study is for the methods used within the scope of the study to be easily applicable, evaluable with quantitative data, having abundant studies in the literature, and being a continuously evolving field.

Methodology

One of the primary goals of construction project management is to create more economical and resilience structures, which requires proper material sourcing. This study examines concrete supply, which constitutes a significant portion of construction costs.

There are many studies in the literature related to supplier selection. In this study, the selection of the TOPSIS method is based on the simplicity of mathematical operations and the ease of achieving the desired outcome. In addition, by integrating the TOPSIS method with the concept of fuzzy logic, linguistic expressions used in data evaluation are quantified.

TOPSIS, a multi-criteria decision-making method developed by Hwang and Yoon in 1981, was used in a hybrid way with fuzzy numbers by Chen and Hwang in 1992 due to the inadequacy of quantitative expressions in measuring human judgments (Tayyar, 2012). Fuzzy TOPSIS is a useful method in solving problems with a large number of decision makers, uncertainty, and multiple decision criteria (Chen, 2000).

In the Fuzzy TOPSIS method, decision makers are asked to evaluate criteria and alternatives in terms of their compatibility with the flow of life using linguistic expressions. Linguistic evaluations are then converted into triangular, trapezoidal, or trapezoidal fuzzy numbers, and with the calculations made, the proximity coefficients of each alternative are determined. The determined proximity coefficients are ranked, and the appropriate alternative is selected from the alternatives (Tekez & Bark, 2016).

In this study, linguistic variables defined by Chen and triangular fuzzy number correspondences are used in the evaluation of criteria and alternatives: Linguistic expressions and fuzzy number correspondences used in the evaluation of criteria and the variables used for alternatives are shown in Table 1 (Chen, 2000).

Table 1. Linguistic expressions used in the evaluation of criteria and their triangular fuzzy number equivalents (Chen, 2000).

Very Low (VL)	(0.0,0.0,0.1)
Low (L)	(0.0,0.1,0.3)
Medium Low (ML)	(0.1,0.3,0.5)
Medium (M)	(0.3,0.5,0.7)
Medium High (MH)	(0.5,0.7,0.9)
High (H)	(0.7,0.9,1.0)
Very High (VH)	(0.9,1.0,1.0)

Very Bad (VB)	(0, 0, 1)
Bad (B)	(0, 1, 3)
Poor (P)	(1, 3, 5)
Moderate (M)	(3, 5, 7)
Good (G)	(5, 7, 9)
Very Good (VG)	(7, 9, 10)
Excellent (E)	(9, 10, 10)

Case Study

The Fuzzy TOPSIS method has been applied for a sample construction project. The project in question is a heavy industrial structure with a total construction area of 220,000 m². The contractor firm is responsible for material supply, while subcontractor firms are responsible for the implementation part of the construction. The contractor firm oversees every stage of the implementation. The items of construction are received from subcontractor firms after inspections.

A verbal interview was conducted with three authorized individuals, one being the project manager, one being the site manager, and one being the procurement officer, who are decisionmakers in material supply for the contracting company. In the first stage of this interview, 6 alternative suppliers providing ready-mix concrete have been identified. The 6 alternative ready-mix concrete companies considered for evaluation are named as A1, A2, A3, A4, A5, and A6. There are six concrete companies identified, which are reputable in the industry and located near the construction site of the current project. The names of the concrete companies are not provided in the study. Instead, they are represented as A* in the text. In the second stage of the interview, the criteria influencing the decision-making process in supplier selection were evaluated. During the interviews with decision-makers, the most suitable criteria influencing supplier selection in terms of relevant projects and needs were requested to be selected. In this study, 8 main criteria influencing the decision stage were determined from a total of 23 criteria identified by Dickson (1966). In the literature, there are many studies on evaluation criteria used in supplier selection. In this study, the 23-criteria list by Dickson (1966) was utilized as it was considered most suitable for the purpose of the problem. Decision-makers were asked to select the criteria they pay attention to in concrete supply, with a minimum of 8 criteria based on the information provided beforehand. In light of this, decision-makers have identified 8 criteria. The 8 criteria determined are shown in graphic form in Figure 1. In this graphic, K1 represents quality, K2 price, K3 production facilities and capacity, K4 delivery, K5 technical competence, K6 warranty and claims policies, K7 reputation and position in the industry, K8 performance history. Dickson's (1966) supplier selection criteria table was used to determine the criteria for decision makers.

In this study, 8 criteria were identified for use in evaluating the supplier company; quality, price, facility capacity, delivery, technical competence, warranty, reputation, performance history; are grouped as benefit and cost criteria among themselves. In the Fuzzy TOPSIS method, all criteria were considered as benefit criteria and the decision-makers were followed accordingly.

Before moving on to the solution of the decision problem, the hierarchical structure of the problem has been established. The hierarchical structure of the decision problem created for evaluating 6 alternative companies according to 8 specified criteria is shown in Figure 1.

After the hierarchical structure of the problem is established, analyses are conducted using the Fuzzy TOPSIS method, which is a multi-criteria decision-making method.

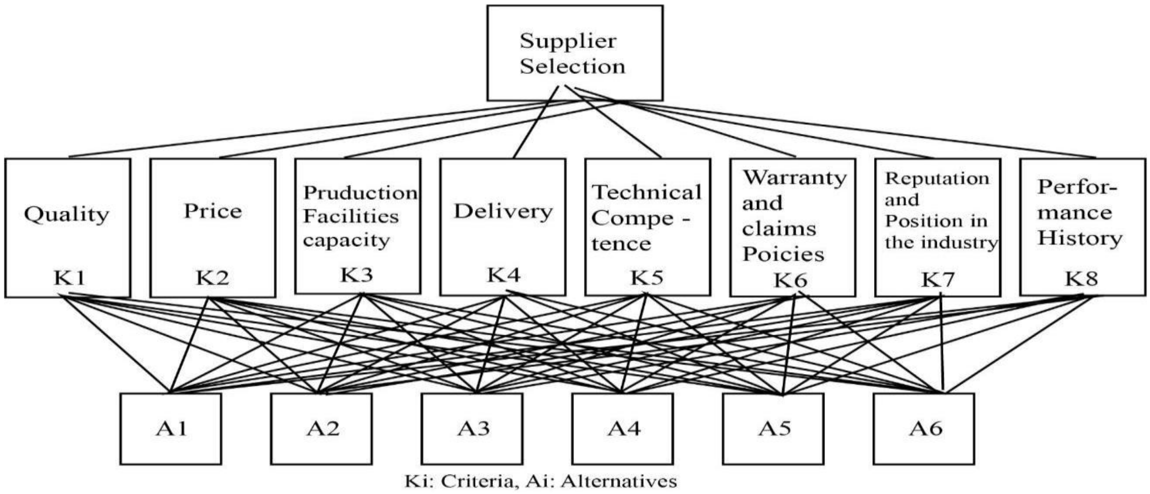

Figure 1: Hierarchical structure of the problem.

Supplier Selection with Fuzzy TOPSIS Method:

Evaluating Decision Makers Decision Criteria with Linguistic Expressions; During the interview with decision-makers, they are asked to evaluate decision-making criteria according to their own importance weights. In the evaluation process, linguistic expressions shown in Table 1 have been used. The evaluation of decision-making criteria with linguistic expressions is shown in Table 2.

Table 2. Evaluation of decision criteria with linguistic expressions.

Criteria	Decision Maker 1	Decision Maker 2	Decision Maker 3
K1	VH	VH	VH
K2	VH	VH	H
K3	H	MH	H
K4	VH	H	VH
K5	H	H	VH
K6	VH	H	H
K7	MH	MH	MH
K8	H	MH	MH

The triangular fuzzy number equivalents of linguistic expressions; and the triangular fuzzy number equivalents of the linguistic evaluations in Table 1 are shown in Table 3.

Table 3. Linguistic expressions of triangular fuzzy number counterparts and weights.

Criteria	Decision-Maker 1	Decision-Maker 2	Decision- Maker 3	Weights
K1	(0.9, 1.0, 1.0)	(0.9, 1.0, 1.0)	(0.9, 1.0, 1.0)	0.9, 1, 1
K2	(0.9, 1.0, 1.0)	(0.9, 1.0, 1.0)	(0.7, 0.9, 1.0)	0.83, 0.97, 1
K3	(0.7, 0.9, 1.0)	(0.5, 0.7, 0.9)	(0.7, 0.9, 1.0)	0.63, 0.83, 0.97
K4	(0.9, 1.0, 1.0)	(0.7, 0.9, 1.0)	(0.9, 1.0, 1.0)	0.83, 0.97, 1
K5	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)	(0.9, 1.0, 1.0)	0.77, 0.93, 1
K6	(0.9, 1.0, 1.0)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)	0.77, 0.93, 1
K7	(0.5, 0.7, 0.9)	(0.5, 0.7, 0.9)	(0.5, 0.7, 0.9)	0.5, 0.7, 0,9
K8	(0.7, 0.9, 1.0)	(0.5, 0.7, 0.9)	(0.5, 0.7, 0.9)	0.57, 0.77, 0.93

Evaluation of Alternatives with Linguistic Expressions; Decision makers were asked to use linguistic variables in evaluating alternatives. The linguistic variables to be used and their triangular fuzzy number equivalents were taken from Table 1.

Creating a Fuzzy Numbers Table Corresponding to Linguistic Expressions; The data in Table 2 was used to identify triangular fuzzy numbers corresponding to the linguistic expressions used by decision makers when evaluating alternatives. The calculated importance weights of the criteria are shown numerically in Table 3.

Creation of the Fuzzy Decision Matrix; The fuzzy decision matrix has been created using the values where decision makers evaluate alternatives in Table 4.

Table 4. Fuzzy decision matrix.

Criteria	Alt.:1	Alt.:2	Alt.:3	Alt.:4	Alt.:5	Alt.:6
K1	(8.3, 9.7, 10)	(7.7, 9.3, 10)	(6.3, 8.7, 9.3)	(7, 8.7, 9.7)	(3.7, 5.7,7.7)	(3.7, 5.7,7.7)
K2	(5.7, 7.7, 9.3)	(7.7, 9.3, 10)	(7, 9, 10)	(3.7, 5.7,7.7)	(7, 9, 10)	(8.3, 9.7, 10)
K3	(7, 9, 10)	(8.3, 9.7, 10)	(5.7, 7.7, 9.3)	(8.3, 9.7, 10)	(3.7, 5.7,7.7)	(3, 5, 7)
K4	(6.3, 8.3, 9.7)	(7.7, 9.3, 10)	(5, 7, 9)	(7, 9, 10)	(3.7, 5.7,7.7)	(5, 7, 9)
K5	(5.7, 7.7, 9.3)	(6.3, 8.3, 9.7)	(3.7, 5.7, 7.7)	(7.7, 9.3, 10)	(5.7, 7.7,9.3)	(3.7, 5.7,7.7)
K6	(6.3, 8.3, 9.7)	(7.7, 9.3, 10)	(7, 9, 10)	(7.7, 9.3, 10)	(5.7, 7.7,9.3)	(4.3, 6.3,8.3)
K7	(7.7, 9.3, 10)	(7, 9, 10)	(5.7, 7.7, 9.3)	(7.7, 9.3, 10)	(3.7, 5.7,7.7)	(3, 5, 7)
K8	(7.7, 9.3, 10)	(8.3, 9.7, 10)	(3.7, 5.7, 7.7)	(7.7, 9.3, 10)	(4.3, 6.3,8.3)	(3.7, 5.7,7.7)

Calculation of Distances to the Fuzzy Positive Ideal Solution Set and Fuzzy Negative Ideal Solution Set; In the model applied in the study by Chen (2000), (A*) represents the fuzzy positive ideal solution, (A-) represents the fuzzy negative ideal solution, and n = 8.

$$(A^*) = [\ (1,1,1), (1,1,1), (1,1,1), (1,1,1), (1,1,1), (1,1,1), (1,1,1), (1,1,1)\ ]$$
$$(A^-) = [\ (0,0,0), (0,0,0), (0,0,0), (0,0,0), (0,0,0), (0,0,0), (0,0,0), (0,0,0)\ ]$$

is accepted as.

The distances to the fuzzy positive ideal set calculated for each criterion of the alternatives are shown in Table 5, and the distances to the fuzzy negative ideal solution set are shown in Table 6. In the formulas, n represents the number of criteria, and m represents the number of alternatives. In this study, since the number of criteria is 8, n = 8, and since the number of alternatives is 6, m = 6.

Table 5. Distances of alternatives to the positive ıdeal solution set.

Criteria	d(Alt.:1, A^*)	d(Alt.:2, A^*)	d(Alt.:3, A^*)	d(Alt.:4, A^*)	d(Alt.:5, A^*)	d(Alt.:6, A^*)
K1	0,1456	0,1831	0,2670	0,2279	0,4800	0,4800
K2	0,3416	0,2160	0,2520	0,4971	0,2520	0,1804
K3	0,3528	0,2955	0,4286	0,2955	0,5583	0,6058
K4	0,2955	0,2160	0,3894	0,2520	0,4971	0,3894
K5	0,3675	0,3241	0,5142	0,2494	0,3675	0,5142
K6	0,3241	0,2494	0,2830	0,2494	0,3675	0,4622
K7	0,4125	0,4357	0,5013	0,4125	0,6129	0,6537
K8.	0,3675	0,3416	0,5855	0,3675	0,5426	0,5855

d(Alt.i, A*): Distance to Positive Ideal Solution Set

Table 6. Distances of alternatives to the negative ıdeal solution set.

Criteria	d(Alt.:1, A^-)	d(Alt.:2, A^-)	d(Alt.:3, A^-)	d(Alt.:4, A^-)	d(Alt.:5, A^-)	d(Alt.:6, A^-)
K1	0,9123	0,8845	0,8070	0,8332	0,5825	0,5825
K2	0,7401	0,8607	0,8361	0,5719	0,8361	0,8861
K3	0,7513	0,7878	0,6711	0,7878	0,5248	0,4717
K4	0,7878	0,8607	0,6932	0,8361	0,5719	0,6932
K5	0,7238	0,7692	0,5617	0,8375	0,7238	0,5617
K6	0,7692	0,8375	0,8152	0,8375	0,7238	0,6203
K7	0,6792	0,6657	0,5983	0,6792	0,4715	0,4250
K8	0,7238	0,7401	0,4980	0,7238	0,5480	0,4980

d(Alt.i, A-): Distance to Negative Ideal Solution Set

The sum of distances to the positive ideal solution set di* and the sum of distances to the negative ideal solution set di- have been calculated and shown in Table 7.

Table 7. Values of di* and di- alternatives

	Alt.:1	Alt.:2	Alt.:3	Alt.:4	Alt.:5	Alt.:6
di*	2.6071	2.2612	3.2209	2.5511	3.6779	3.8711
di^-	6.0877	6.4062	5.4805	6.1070	4.9825	4.7384

The proximity coefficients of each alternative were calculated along with the values of (di*) and (di-) distances. The proximity coefficients of each alternative calculated are shown in Table 8.

Table 8. Proximity coefficients of alternatives.

Proximity Coefficients	Formula	Proximity Coefficient Values	Preference Ranking
C1	6.0877/ (6.0877+ 2.6071)	0.7002	3
C2	6.406/ (6.4062+ 2.2612)	0.7391	1
C3	5.4805/ (5.4805+ 3.2209)	0.6298	4
C4	6.1070/ (6.1070+ 2.5511)	0.7053	2
C5	4.9825/ (4.9825+ 3.6779)	0.5753	5
C6	5.7384/ (4.7384+ 3.8711)	0.5504	6

Ci: Proximity Coefficient of Alternative

Ranking of Proximity Coefficients of Alternatives and Preference Ranking; The ranking of proximity coefficient values shown in Table 8 from largest to smallest is C2>C4>C1>C3>C5>C6.

Conclusion and Discussion

As a result, in this study, errors that may arise from the personal opinions of decision-makers in the selection of ready-mix concrete necessary for more durable structures have been minimized, and a consensus has been reached through collective wisdom. Studies that operate the decision-making mechanism in construction project management with collective wisdom will enable project managers to make fewer mistakes and build more environmentally friendly, more economical, and more durable structures.

As a result of this study, A2 company has been selected as the best concrete company among the alternatives. It is recommended to use similar integrated methods in other material supplies, labor supplies, financial and management decisions in the project.

In the example taken, a solution was made using the fuzzy TOPSIS method. The process steps were followed through verbal interviews with three individuals in decision-making positions in the relevant project. Criteria they pay attention to in evaluating alternatives were determined, and after the alternatives were identified, all team members were asked to evaluate them using linguistic expressions. A solution was made using the fuzzy TOPSIS method and the proximity coefficients of the alternatives were determined. In this study, option A2 emerges as the most suitable choice. The worst option is option A6.

In the construction sector, the supply of ready-mixed concrete and construction steel in rough construction manufacturing have significant costs. Therefore, efforts aimed at reducing costs and improving quality in this area are highly valuable.

In conclusion, it is explained that fuzzy logic-based MCDB methods can be used in solving supplier selection problems in this study. It is considered that other methods not used in advanced studies can be evaluated and compared. In cases where the number of decisionmakers is high, it is evaluated that fuzzy MCDB methods can be used and can be the subject of further studies. It is expected that more precise results will be obtained with sensitivity analyses that are not performed within the scope of this study but can be performed in future studies.

References

Chen (2000). Extensions of the TOPSIS for Group Decision – Making Under Fuzzy Environment. *Fuzzy Sets and Systems*, 114(1), 1-9.

Celik, F. & Cagil, G. (2021). Supplier Selection with Fuzzy Multi-Criteria Decision-Making Techniques: An Example of Tractor Factory. *Dokuz Eylul University Faculty of Engineering Journal of Science and Engineering*, 23(68), 607-619.

Dagdeviren, M. & Eraslan, E. (2008). Supplier Selection Using PROMETHEE Sequencing Method. *Journal of the Faculty of Engineering and Architecture of Gazi University*, 23(1), 6975.

Gokalp, B. & Soylu, B. (2011). Supplier Selection Problem with the aim of Improving Supplier's Processes. *Journal of Industrial Engineering (Turkish Chamber of Mechanical Engineers)*, 23(1), 4-15.

Polat, G. - Eray, E. & Bingöl, B.N. (2017). An Integrated Fuzzy MCGDM Approach for Supplier Selection Problem. *Journal of Civil Engineering and Management*, 23(7), 926-942.

Supciller, A. A. & Deligoz, K. (2018). Compromise Solution of Supplier Selection Problem by Multi Criteria Decision Making Methods. *International Journal of Economics and Administrative Studies*, 355-368.

Tayyar, N. (2012). Fuzzy AHP and Fuzzy TOPSIS Approach to Pet Bottle Supplier Selection. *Suleyman Demirel University the Journal of Faculty of Economics and Administrative Sciences*, 17(3), 351-371.

Tekez, E. & Bark, N. (2016). Supplier Selection for Furniture Industry with Fuzzy TOPSIS Method. *Sakarya University Journal of Science*, 20(1), 55-63.

Ugur, L. O. (2017). Construction Project Manager Selection with the MOORA Optimization Method: A Multi-Objective Optimization Application. *Journal of Polytechnic*, 20 (3), 717-723.

Zadeh, L. A. (1965). Fuzzy Sets. *Information and Control*, 8(3), 338-353.

Value Engineering in Construction Projects of Turkey

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Abstract

Successful completion of construction projects relies on timely completion, adherence to budget constraints, and the delivery of expected quality. The construction industry faces heightened competition amid economic downturns and currency fluctuations. Many countries have turned to value engineering to address industry challenges. In our country, where inflation is high and exchange rates fluctuate, similar to other nations, budgetary savings through value engineering have not been realized, and there have been limited studies on the subject.

The goal is to boost the implementation of value engineering in Turkish construction projects by uncovering its contributions as identified in existing literature. A survey was applied to architects and engineers who have worked or are currently working in the construction industry of Turkey. The survey aims to assess awareness, knowledge, and experience levels regarding value engineering in Turkey, benefits and challenges associated with its use. By analyzing survey results alongside literature findings, recommendations will be presented for the application of value engineering in Turkey.

Keywords: *construction project, value engineering, value engineering applications*

Introduction

The increasing competition in the business world, worsening economic conditions, and diminishing natural resources have led to various pursuits in the construction sector. Value engineering is one of the widely used techniques in response to these challenges (Dikmeoglu, 2018). For half a century, value engineering has been applied in construction projects with the aim of providing innovative ideas and solutions to enhance project value (Masengesho, et. al., 2021). Since the 1950s, value engineering has become a common practice in advanced countries for many government agencies as well as private engineering firms and contractors.

In our country, many contracts in the construction sector are governed by the Public Procurement Contracts Law (PPCL) (Çakmak, 2014). Public procurement contracts are used for all construction works carried out in the public sector. The implementation of value engineering in public procurement contracts could positively contribute to the entire construction sector. It has been observed that in our country, where inflation is high and exchange rates show sudden fluctuations, budget savings are not achieved through value engineering, and there is very little research conducted on value engineering. By uncovering the contributions of value engineering in the construction sector from existing literature, the aim is to contribute to the increase in the application of value engineering practices in construction projects in Turkey.

Method of Study

The steps of the study's methodology can be seen in Figure 1.

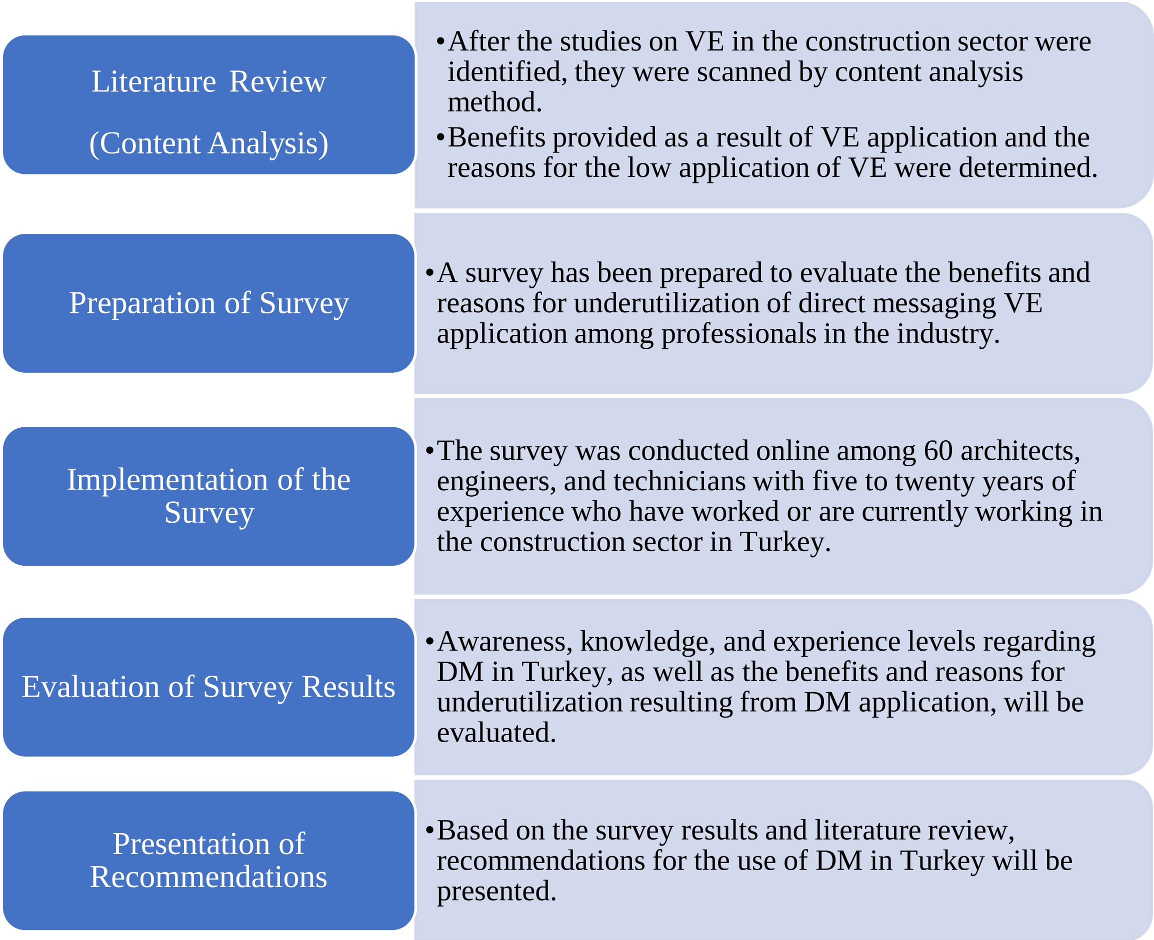

Figure 1: Steps of methodology.

Literature Review (Content Analysis)

The contributions of value engineering in the construction sector were evaluated using the existing literature content analysis method. A total of 65 publications between 1983 and 2022 discussing the contributions of value engineering in the construction sector were accessed from Web of Science and Science Direct. The analysis revealed that the contributions of value engineering in the construction sector are identified as follows: reducing costs, improving performance and scope, benefiting environmental protection, supporting the use of new technologies, shortening project duration, enhancing the functional benefits of design, and increasing overall value and quality. Among the 65 publications accessed from Web of Science and Science Direct, cost reduction was mentioned 48 times, improvement of performance and scope 23 times, environmental benefits 10 times, support for new technology use 14 times, shortening project duration 9 times, enhancing the functional benefits of design 12 times, and increasing overall value and quality 33 times. The most frequently mentioned benefit in the literature was identified as cost reduction and increasing overall value and quality (Ozbas, 2023).

An analysis of 65 publications accessed through Web of Science and Science Direct revealed that six of them included surveys. These surveys contributed to the preparation of the survey instrument by evaluating the questionnaire items used in previous studies. Fong (1998) conducted a survey targeting employers to measure their knowledge and experience regarding value engineering. Chen et al. (2010) conducted a survey investigating the importance of the value engineering team and work plan in VE implementation. Shaikh, Shabir and Memon (2015) asked questions regarding the problems and reasons for the low implementation of value engineering. Gunduz et al. (2022) administered a survey to determine at which stage of the project value engineering implementation would be more beneficial and to identify the importance of value engineering implementation during the design phase. Cheah and Ting (2004) identified the main barriers encountered in value engineering implementation.

The other questions in the survey addressed the reasons for the low implementation of value engineering, determining the procurement/tendering systems that enable value engineering implementation, and assessing the approach of firms with different job descriptions towards value engineering. Bowen, et al. (2010) evaluated the importance of the benefits of value engineering implementation, such as reducing costs, increasing the value of project functions, facilitating bid preparation, producing environmentally friendly projects, enabling flexible project design, and reducing project duration. Additionally, survey participants were asked to rate the benefits of value engineering to customers in terms of time, comfort, flexibility, and environmental benefits.

The Preparation and Implementation of the Survey

Literature review results regarding the contributions of value engineering (VE) practices in the construction sector were utilized to prepare a survey aimed at professionals’ assessment in the construction sector of Turkey. The reasons for the limited use of VE practices were also assessed. The survey first inquired about the participants' experience in the sector and whether they had implemented VE practices. A 5-point Likert scale was used for assessing the importance levels in the survey questions. The scoring related to the 5-point Likert scale is presented in Table 1.

Table 1. Scoring for the 5-point Likert scale.

Importance Level	Scale for Importance
5	Strongly Agree
4	Agree
3	Neutral
2	Disagree
1	Strongly Disagree

An online survey was conducted using Google Forms and was sent to 60 architects, civil engineers, or technicians who have worked or are currently working in private construction companies in Istanbul and in public construction tendering processes. The survey participants are experienced individuals in the sector, primarily with expertise in building and site projects. Individuals who have worked in corporate firms were predominantly included in the survey.

Assessment of Survey Results

The data obtained from the survey were statistically analyzed. For questions assessing the importance levels, respondents were asked to rate their responses on a scale from 1 to 5, where 1 represents the lowest importance and 5 represents the highest. The weighted averages of the responses were calculated based on the scores assigned by the respondents according to the importance levels. These weighted averages were then normalized, and percentile values were also calculated.

Knowledge and Experience Level Regarding VE

61.67% of the respondents to the survey are knowledgeable about value engineering, while 38.33% do not have sufficient knowledge about it. Among the respondents, 38.33% have experience with value engineering applications, while 61.67% do not. Among those who have conducted value engineering applications, 48% are individuals with more than 20 years of experience. Among those who have conducted value engineering applications, individuals with less than 5 years, 5-10 years, 11-15 years, and 16-20 years of experience are distributed at rates of 13% each.

Benefits Achieved through VE Application

In Table 2, the evaluation of 60 professionals operating in the construction sector in Turkey regarding the benefits achieved through the Value Engineering (VE) application is observed. With a score of 4.55 points, “meeting customer expectations” has been identified as the most important benefit. The participants in the survey evaluated “increasing the project's value” with 4.50 points, "reducing energy consumption” with 4.45 points, “reducing costs,” “reducing environmental pollution,” “carrying out the project efficiently” and “successful risk management” with 4.43 points each, “achieving the project's optimum lifespan” with 4.35 points, “improving quality” with 4.33 points, “providing flexibility to the project” with 4.27 points, “reducing operating costs of the project” with 4.23 points, and “increasing the project's prestige” and “shortening the project's duration” with 4.20 points each. It was observed that the benefits achieved through VE application have similar values. The results obtained indicate that the VE application is highly beneficial for each identified benefit.

Table 2. Evaluation of benefits achieved through VE application.

	1	2	3	4	5	weighted average	normalized priorities
It is important to meet customer expectations.	0	0	3	21	36	4,55	0,08
It is important to reduce the cost.	0	1	2	27	30	4,43	0,08
It is important to improve the quality.	0	1	5	22	31	4,33	0,08
It is important to increase the project's value.	0	0	4	22	34	4,50	0,08
It is important to achieve the project's optimum lifespan.	0	1	6	24	29	4,35	0,08
It is important to provide flexibility to the project.	0	2	10	18	30	4,27	0,08
It is important that the project is carried out efficiently.	0	0	6	22	32	4,43	0,08
It is important to reduce operating cost of the project	0	1	5	23	31	4,23	0,07
It is important to increase the project's prestige.	0	0	11	26	23	4,20	0,07
It is important to reduce environmental pollution.	0	0	6	22	32	4,43	0,08
It is important that the risk management of the project is successful.	0	0	6	22	32	4,43	0,08
It is important to shorten the duration of the project.	0	1	8	29	22	4,20	0,07
It is important to reduce energy consumption.	0	0	8	17	35	4,45	0,08

*[(1x0)+(2x0)+(3x3)+(4x21)+(5x36)]/60
**4,55/(4,55+4,43+4,33+4,5+4,35+4,27+4,43+4,23+4,20+4,43+4,43+4,20+4,45)

In Figure 2, the evaluation of the benefits of value engineering application is observed for professionals who have and have not implemented the value engineering application. “Carrying out the project efficiently” is considered the most important benefit by professionals who have not implemented the application, with a score of 4.70 points, while it is evaluated as the least important benefit by professionals who have implemented the application, with a score of 4.00 points. “Increasing the project's value” and "meeting customer expectations" are considered the most important benefits by professionals who have implemented the application, with a score of 4.65 points. “Successful risk management” is evaluated equally by professionals who have and have not implemented the application.

In the literature review conducted using content analysis method, the most frequently mentioned benefit obtained because of VE application has been cost reduction. The second most frequently mentioned benefit, on the other hand, has been determined as the increase in total value and quality. According to the survey results, professionals who have implemented

VE consider "increasing the project's value" and "meeting customer expectations" as the most important benefit. They have regarded "cost reduction" as equivalent to many other benefits.

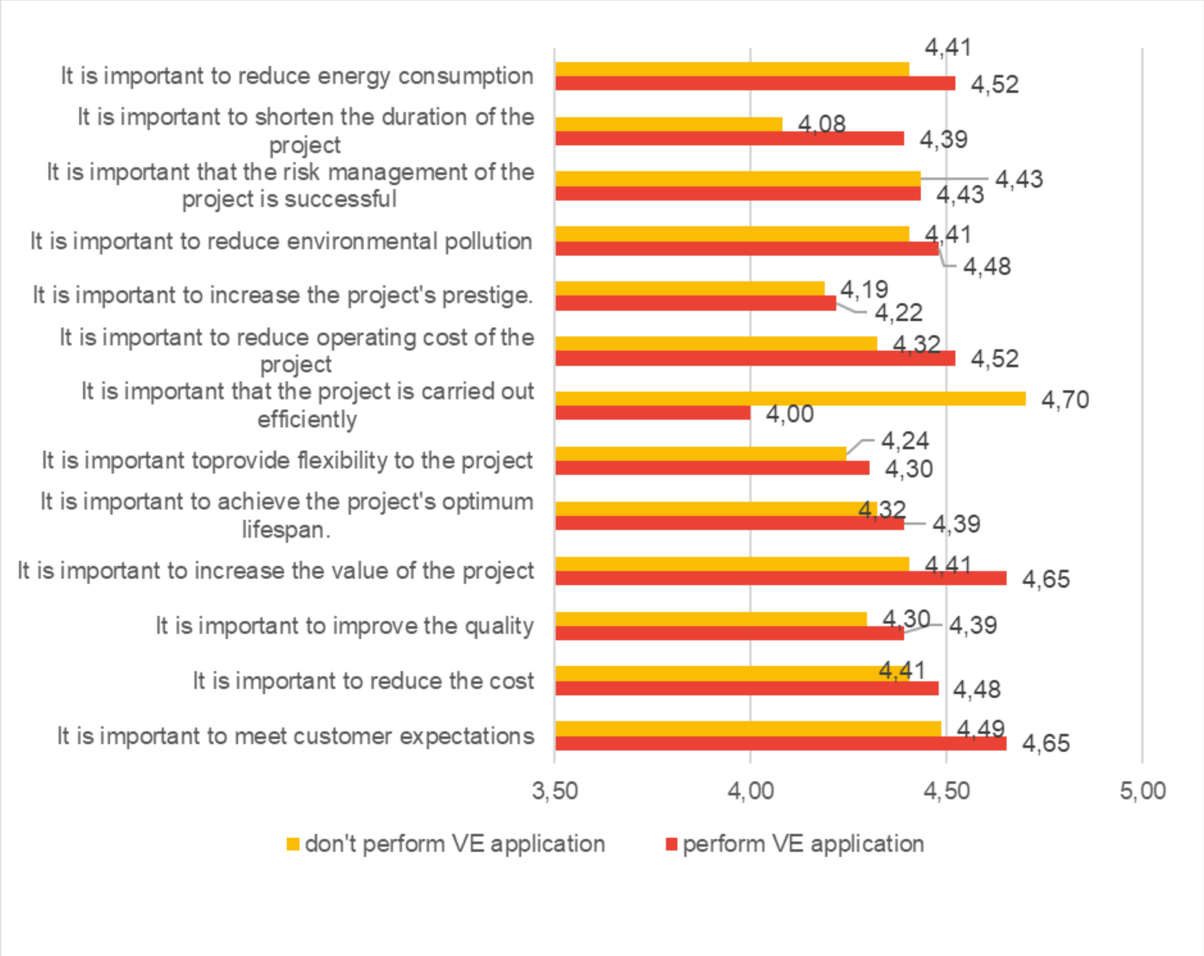

Figure 3: Evaluation of the benefits achieved as a result of VE application for those who have and have not performed VE application.

Evaluation of the Reasons for the Low Utilization of VE in Construction Projects

In Table 3, the participants evaluated the reasons for the low implementation of Value Engineering (VE) based on the survey. According to the respondents, “lack of sufficient knowledge about VE” is the most important reason with a score of 4.25. They rated “lack of support from official institutions” at 3.95 points, “Inflexible attitudes during the project process” at 3.88 points, “Stakeholders not being involved in the process” at 3.78 points, and “Complexity of the VE process” at 3.63 points. The least important reason, with a score of 3.30 points, was “High cost of VE implementation”.

In Figure 3, the evaluation of the reasons for the limited implementation of VE by professionals who have and have not implemented VE is observed. "Lack of sufficient knowledge about VE" has been evaluated as the most important reason by both professionals who have and have not implemented the application. Those who have implemented it rated it as 4.09 points, while those who have not implemented it rated it as 4.35 points. "High cost of VE implementation" has been evaluated as the least important reason by both professionals who have and have not implemented VE.

Table 3. Evaluation of the reasons for the low implementation of VE.

	1	2	3	4	5	weighted average	normalized priorities
VE implementation has a high cost.	1	14	19	18	8	3,3000	0,1447
VE implementation has a complex process.	1	11	10	25	13	3,6333	0,1594
There is lack of sufficient knowledge about VE	1	2	6	23	28	4,2500	0,1864
There is a lack of support from official institutions	0	2	19	19	20	3,9500	0,1732
There are inflexible attitudes during the project process.	1	3	18	18	20	3,8833	0,1703
Stakeholders are not included in the process.	0	5	19	20	16	3,7833	0,1659

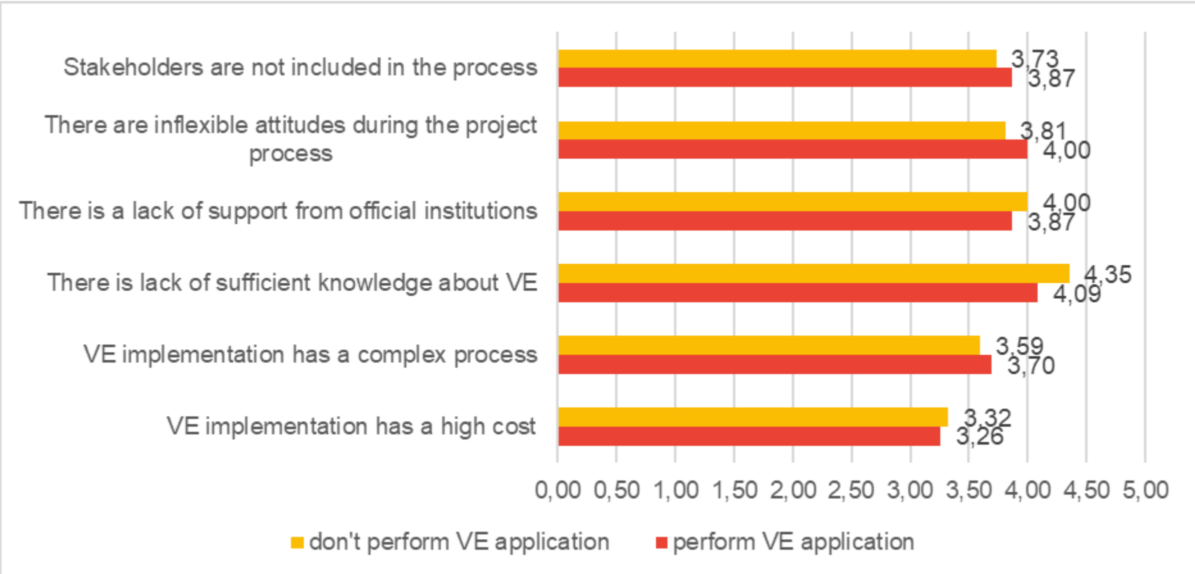

Figure 3: Evaluation of the reasons for the low implementation of Value Engineering (VE) by those who have and have not performed the application.

Conclusion and Recommendations

The lack of information about Value Engineering (VE) contributes to its underutilization. Increased awareness of the importance and benefits of value engineering could lead to more VE applications. In Turkey, Value Engineering is not addressed within the compulsory courses of architecture undergraduate education. Similarly, VE topics are absent from construction management courses and certification programs.

Given the economic situation in Turkey and globally, it is believed that value engineering will gain more importance, particularly with the fluctuations in exchange rates and the European Union accession process. Environmental issues, such as global warming, have made individuals in the construction sector more environmentally conscious. The increasing number of public tenders over the years and the acceptance of the concept of value engineering by young engineers and architects suggest that value engineering will be increasingly used for both economic and environmental sustainability in the coming years.

It is believed that providing more information about value engineering, incorporating it into the curricula of architecture and civil engineering undergraduate programs, including it in the content of certification programs, and raising awareness in the public sector will lead to increased implementation and benefits for the industry.

References

Bowen, P., Edwards, P., Catteil, K., & Jay, I. (2010). The awareness and practice of value management by South African consulting engineers: Preliminary research survey findings. *International Journal of Project Management*, 28, 285–295.

Cheah, C., & Tingb, S. (2004). Appraisal of value engineering in construction in Southeast Asia. *International Journal of Project Management*, 23(2), 151-158.

Chen, WT, Chang, PY, & Huang, YH (2010). Assessing the overall performance of value engineering workshops for construction projects. *International Journal of Project Management*, 28 (5), 514-527.

Çakmak, F. P. (2014). *Türkiye Kamu Yapım İhalelerinde Kullanılan Standart Sözleşme Dökümanlarının Yeniden Yapılanması* [Unpublished doctoral dissertation]. Istanbul Technical University.

Dikmeoglu, N. E. (2018). İnşaat Sektöründe Değer Mühendisliği ve Uygulamaları. *Teknik Bilimleri Dergisi*, 8 (3), 15-22.

Fong, S. W. (1998). Value Engıneerıng In Hong Kong - A Powerful Tool For A Changing Society. *Computers and Industrial Engineering*, 35, 627-630.

Gunduz, M., Aly, A. A., & Mekkawy, T. E. (2022). Value Engineering Factors with an Impact on Design Management Performance of Construction Projects. *Journal of Management in Engineering*, 38(3).

Masengesho, E., Wei, J., Umubyeyi, N., & Niyirora, R. (2021). A Review on the Role of Risk Management (RM) and Value Engineering (VE) Tools for Project Successful Delivery. *World Journal of Engineering and Technology*, 9 (1), 109-127.

Shaikh, P. Shabir, H. K., & Memon, A. A. (2015). Adoption of Value Engineering: An Attribute Study for Construction Industry of Pakistan. *Mehran University Research Journal of Engineering & Technology*, 34 (4), 453-460.

Ozbas, B. (2023). *Kamu İhale Sözleşmelerinde Değer Mühendisliğinin Yeri* [Unpublished master's thesis]. Istanbul Kultur University.

Simulation Models and Tools Use In Decision Making for Construction Projects

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Abstract

Simulation is a modeling technique that creates an infrastructure for observing the properties of a real system in a virtual environment by transferring data belonging to a physical system existing in the real world. Simulation models and tools that enable simulation creation were used for different purposes in the periods of the industrial revolution. Nowadays, simulation models and tools are used in important stages such as "decision making" and "real-time simulation" within the scope of integration with industry 4.0, unlike the traditional simulation usage purpose. This study presents a comprehensive comparative literature review on the application of simulation models and tools to enhance decision-making processes in construction projects within the framework of Industry 4.0. The use of simulation models and tools in a sector such as construction, which carries high risks from many different perspectives, is predicted to be frequently used in the coming years due to its advantages such as minimizing risks, developing sustainable designs, foreseeing necessary precautions and possibilities thanks to accurate decision making without causing high costs and time loss. In this research, the utilization of simulation models and tools in construction projects is investigated through a systematic literature review utilizing the Web of Science and Scopus databases. Following keyword-based searches and bibliometric analysis, a total of 523 relevant papers were identified. The bibliometric network analysis revealed prominent keywords such as risk management, site mobilization, cost management, and waste management, which are intricately linked to the decision-making process in construction projects utilizing simulation models and tools. The bibliometric network analysis revealed prominent keywords such as risk management, site mobilization, cost management, and waste management, which are intricately linked to the decision-making process in construction projects utilizing simulation models and tools. Specifically, simulation methods like hybrid simulation, fuzzy-based System Dynamic simulation, building information model (BIM) are advocated for addressing the time, cost, risk managements in construction projects, while integration of advanced technologies to simulation models and tools.

Keywords: *construction, cost management, decision making, project management, risk management, simulation models and tools, site mobilization, waste management.*

Introduction

The key intent of this work is to present a comprehensive comparative literature survey of uses simulation models and tools for accurate decision-making processes in construction projects. Simulation, which has been the subject of research and publications from the 1930s to the present day, encompasses various meanings depending on the industry and purpose for which it is used. These meanings include “prediction”, “decision-making”, “design-modeling”, “visualization” and “virtual entertainment”. Bungartz et al. (2014) emphasize that in today’s context, simulations do not necessarily refer to computer simulations that mimic the entire processes of specific real-world scenarios. Instead, they create a “virtual experimental” environment using simulation tools and relevant experts, particularly for applications where real-world experiments are impossible due to temporal and spatial constraints. Kuruoglu et al. (2000) defines simulation as the process of creating a model that replicates the behavior of a real system, enabling the observation of its performance or evaluating alternative strategies.

Landriscina (2013) suggests that rather than modeling an entire system through simulation, it can be more effective to selectively reproduce certain aspects of the system in terms of form or content. Based on the definitions obtained from all these studies, simulation can be summarized in English as an interactive tool that transforms real-world systems into virtual systems for various purposes, enabling experiments and trials. For summary, these definitions of simulation models and tools show facilitates the creation of a “virtual experimental” environment, particularly for applications where real-world experiments are impractical due to temporal and spatial constraints.

The concept of Industry 4.0, also known as the Fourth Industrial Revolution, was introduced at the Hannover Fair in 2011 as a component of Germany's strategic initiative aimed at enhancing the competitiveness of its manufacturing industry in the long term (Liao et al., 2017). Armellini et al. (2020), Industry 4.0 is to reduce risks and costs by increasing performance by transforming complex production systems in the systems road map into smart production systems (Celen, 2017). After 2013, I4.0 gained worldwide recognition and became a hot topic in scientific literature (Liao et al., 2017). Simulation is a key technology for developing planning and exploratory models to optimize decision making as well as the design and operations of complex and smart construction project.

Simulation models are progressively employed to facilitate crucial decision-making processes in construction engineering. Akhavian and Behzadan 2013, Among the numerous simulation methodologies accessible, discrete-event simulation (DES) is predominantly utilized in industrial and infrastructure construction decision-making contexts due to its capacity to simulate resource interactions and operational logistics, particularly in the context of extensive and intricate construction projects. Risk management constitutes a fundamental aspect of construction projects, where the outcome's success or failure hinges on the risk management approach undertaken (Nasirzadeh et al., 2008).

Construction projects increasingly employ a strategy that involves using simulation and modeling techniques to make decisions, covering various aspects such as risk, site mobilization, cost, and waste management. (Nasirzadeh et al., 2008; Rahimian et al., 2020; Yuan et al., 2016).

Exploring the Applications of Simulation Models and Tools in the Era of Industry 4.0

Erkut (1992) defines simulation as the process of creating a model that replicates the behavior of a real system, enabling the observation of its performance or evaluating alternative strategies. Simulation models and tools have a broad range of industrial applications, encompassing education, healthcare, services, manufacturing, operations, management, and marketing activities (Celen, 2017).

The research areas using the "simulation models and tools" keyword in Scopus can be seen in Figure 1. According to Figure 1, the most researched areas of simulation models and tools are seen as Engineering (30,2%), Computer Science (17,6%) in 14,941 papers. Figure 1. (b) shows the publication year distributions, peak point in 2010 with 1,353 papers, 2011 follows with 1,306 papers.

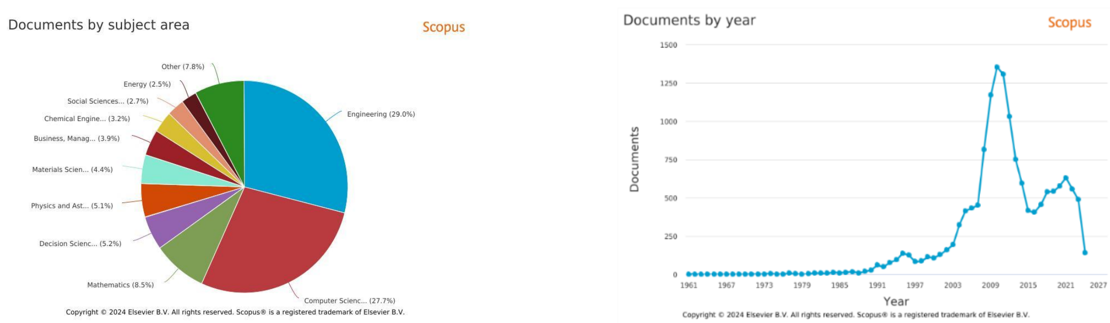

Figure 1: The research areas of Simulation models and tools (a) and their publication distrubutions (b).

The Industry 4.0, i.e., the Fourth Industrial Revolution, is a term conceived at the Hannover Fair in 2011 as part of Germany's long-term strategy to strengthen the competitiveness of its manufacturing sector (Liao et al., 2017). Simulation is a key technology for developing planning and exploratory models to optimize decision making as well as the design and operations of complex and smart production systems (de Paula Ferreira et al., 2020). In the other hand, simulation models are becoming increasingly used to evaluate critical decision making in construction engineering (Wu et al., 2019). It could also aid companies to evaluate the risks, costs, implementation barriers, impact on operational performance, and roadmap toward Industry 4.0 (de Paula Ferreira et al., 2020).

The research areas using the "Simulation" and "Industry 4.0" keywords in Scopus can be seen in Figure 2. According to Figure 2, the research area of "Decision Sciences" (5.2%) -which is not included in before Industry 4.0 (Figure 1.)- ranks fourth among the most researched subjects. Figure 2 (b) shows the publication year distributions, peak point in 2022 with 649 papers, 2023 follows with 564 papers. Data show that advent of Industry 4.0, the use of simulation models and tools has expanded to include "decision making." Over the past decade, there has been a growing trend in research publications related to "Simulation" and "Industry 4.0" keywords.

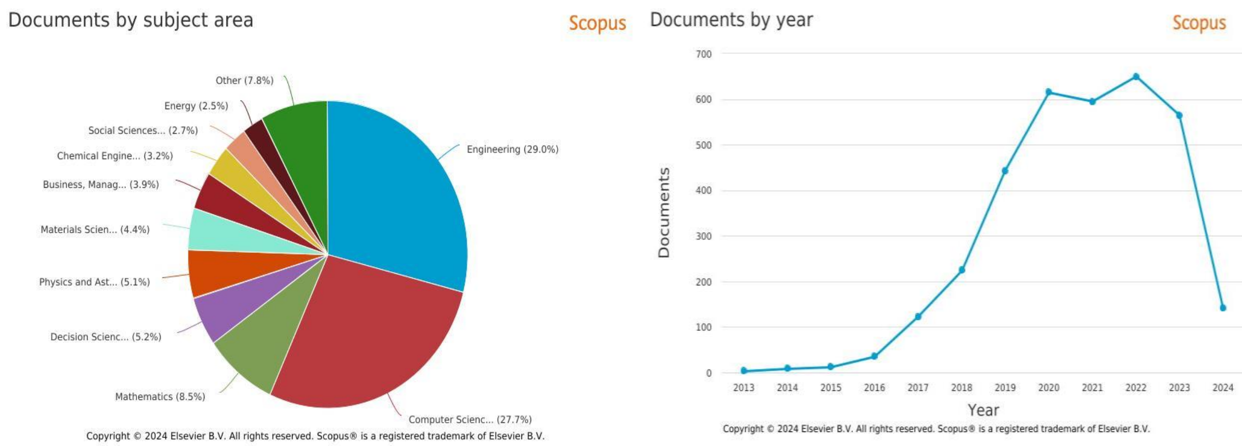

Figure 2: The research areas of Simulation with Industry 4.0 (a) and their publication distrubutions (b).

According to de Paula Ferreira et al. (2020) literature review about "Simulation in industry 4.0" shows that 10 simulation-based approaches are used in the context of Industry 4.0 (Figure 3): Discrete event simulation (DES), System Dynamics (SD), Agent-Based Modeling and Simulation (ABMS), Hybrid Simulation (HS), Petri Nets Simulation (PN), Artificial Intelligence (AI), Virtual Reality (VR), Augmented Reality (AR), Virtual Commissioning (VC), and Digital Twins (DT).

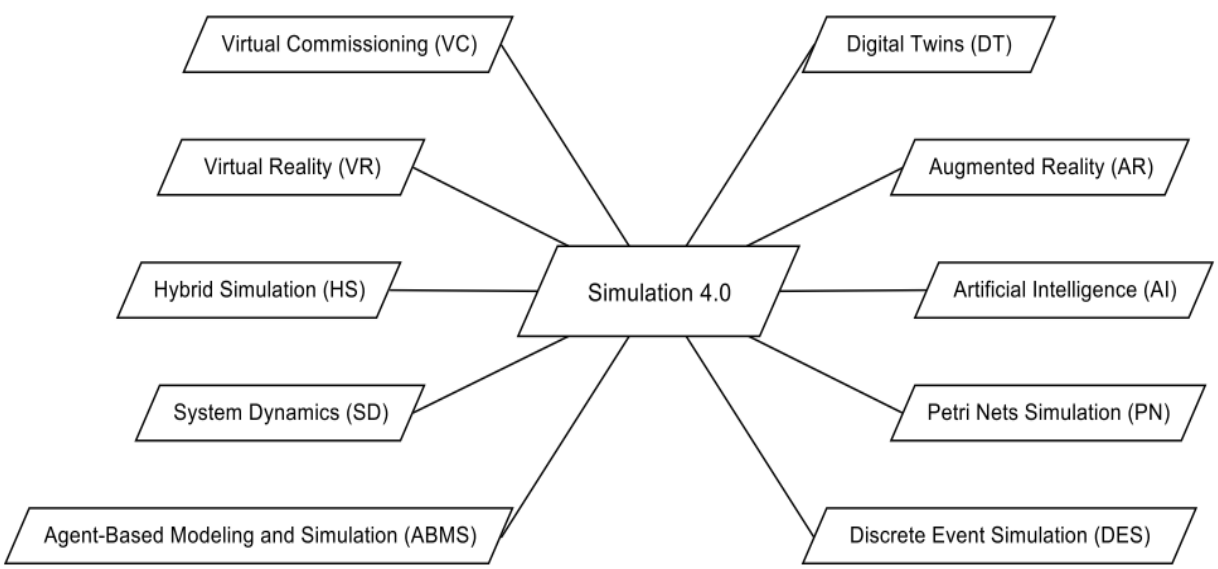

Figure 3: Simulation-based approaches applied in Industry 4.0 (de Paula Ferreira et al., 2020).

This result indicates that traditional simulation techniques (e.g., DES, SD) and software tools (e.g., Arena, Anylogic, Simulink) are still applicable in I4.0. The results also indicate hybrid simulation and digital twin as the main simulation approaches in the context of I4.0 (de Paula Ferreira et al., 2020).

Research Methodology

Simulation models and tools are used in cost, time and risk management of construction projects because of the advantage of following the construction stages. (Celen, 2017). These models and tools are used in different industries as a part of decision making phase with the Industry 4.0 (Oliveira et al., 2016; Liao et al., 2017). In this research, the place of the use of simulation models and tools in construction projects is investigated through systemmatic literature review.

A comprehensive literature review was conducted to examine in detail the existing studies on simulation models and tools with decision making and its applications in construction projects. During the literature review, Web of Science and Scopus databases were utilized. Using the keywords "simulation models and tools," "construction project," and "decision making" in the title/abstract/keywords domain, a collection of 272 papers (N) was gathered from Web of Science, and 339 papers (N) from Scopus. The obtained papers were then processed through EndNote Web to remove duplicates. After duplicate removal, a total of 523 papers (N) were obtained. These 523 papers (N), obtained through EndNote Web after reconciling the two different databases, were exported in EndNote format to conduct bibliometric search, scientometric mapping, and analysis. VOSviewer software was used for this purpose.

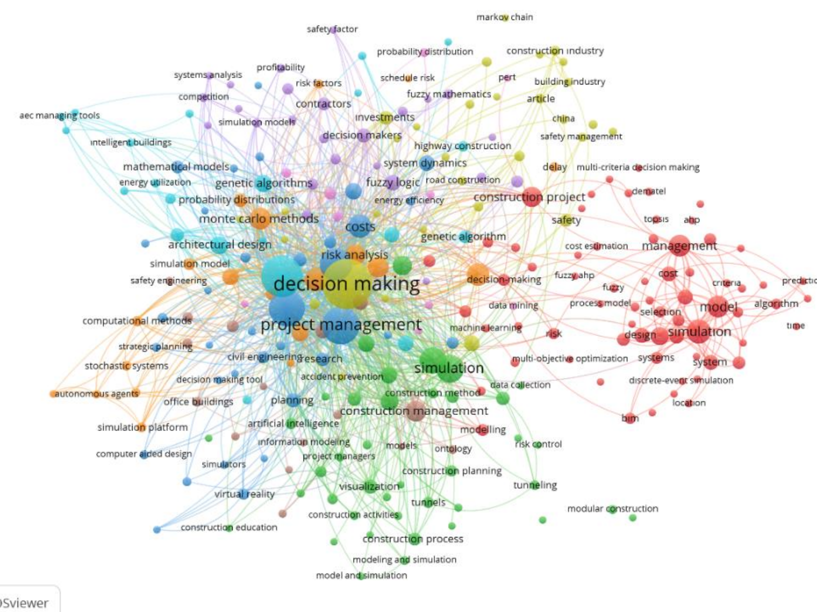

Figure 4: The bibliometric network of “simulation models and tools”, “construction project”, “decision making” and related keywords by VOSviewer (2024).

The bibliometric network illustrating the relationships between the keywords "simulation models and tools," "construction project," and "decision making," published between 1971 and 2024, is shown in Figure 4, obtained using VOSviewer.

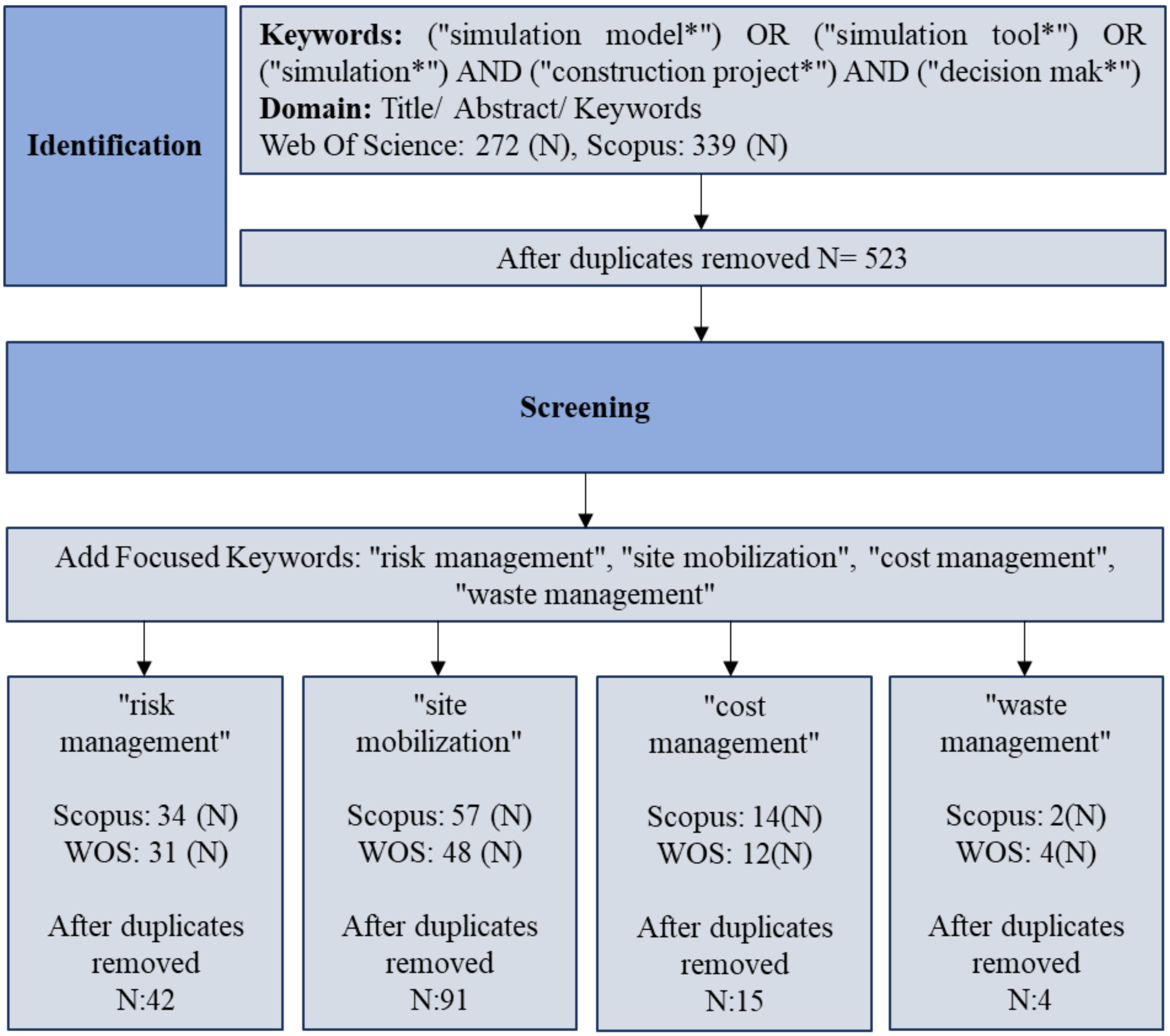

Figure 5: Framework of literature review strategy.

Upon examining the bibliometric network generated in Figure 4, it is observed that simulation models and tools in construction projects are frequently associated with decision making through four focused keywords: "risk management," "site mobilization," "cost management," and "waste management."

The publications obtained based on the identified keywords were further screened using the focused keywords. A literature review was conducted through Web of Science and Scopus databases, and duplicates were removed using EndNote Web. As depicted in Figure 5, the strategy of this literature review is described, and after duplicates were removed, the following numbers of papers (N) were obtained when each focused keyword was added: 42 papers for "risk management," 91 papers for "site mobilization," 15 papers for "cost management," and 4 papers for "waste management." The relationship between these concepts and studies will be examined in the Findings section.

Findings

Decision Making with Simulation in Construction Projects & Risk Management: In the 42 articles obtained through this literature review, discussions revolve around enhancing decision-making processes in the field of risk management within construction project. Techniques such as modeling complexity-driven risk paths, system dynamics, fuzzy logic modeling, and multi-agent modeling are utilized to address risk management in construction projects. The focus rests on the two most cited articles related to decision making in risk management.

Risk management is an important and integral part of construction project. The success or failure of a construction project may vary depending on the approach that is adopted toward managing the risks (Nasirzadeh et al., 2008). In construction projects, analyzing existing risks alone is insufficient. This is because construction projects can encounter dynamic and flexible risks, and risk management should be prepared for scenarios where such risks may arise. Successfully managing risk throughout all phases of construction for a bridge to be built over a lake involved using a fuzzy-based System Dynamic simulation method. This approach helped mitigate the adverse effects of internal and external potential risks (Nasirzadeh et al., 2008).

Qazi et al. (2017) says that, Project complexity has been a focal point of extensive research in the literature due to its significant impact on the success or failure of major projects. These complexities often lead to cost and time overruns.

We consider the decision problem of identifying critical risks and selecting optimal risk mitigation strategies at the commencement stage of a project, taking into account the utility function of the decision maker with regard to the importance of project objectives and holistic interaction between project complexity and risk (Qazi et al., 2017).

AHP, Fuzzy Set Theory (FST) and hybrid methods integrating the two techniques have been extensively used in modelling project complexity due to their prominence in the literature on project risk management. However Qazi et al. (2017) suggests that, proposed a new process in order to identify the complexity attributes in construction projects and the risks they cause to select the most optimal risk mitigation strategies.

As indicated Figure 6. researchers have been using different techniques for capturing interdependency between decision making with simulation in construction projects and risk management.

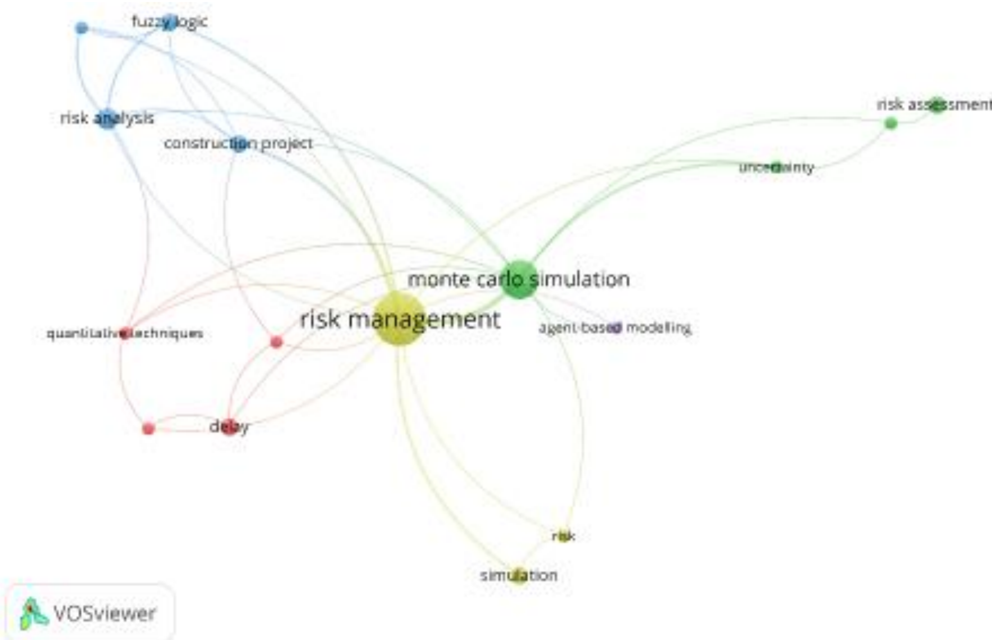

Figure 6: The bibliometric network of focused keyword “risk management” by VOSviewer.

Decision Making with Simulation in Construction Projects & Site Mobilization: In the 91 articles obtained through literature review, the enhancement of decision-making processes in site mobilization for construction projects is discussed. This enhancement is achieved through the integration of GPS data for real-time equipment operation analysis, building information modeling (BIM) and machine learning, decision support systems for crane selection, and similar techniques. The focus rests on the four most cited articles related to decision making with site mobilization.

Site Mobilization is an important and early phases of construction project. Pradhananga and Teizer (2013) focuses on analyzing construction site operations using GPS data. It aims to improve construction project efficiency and resource allocation through continuous spatio-temporal analysis with construction simulation. So that way, construction managers that allow decision makers at all levels in construction take advantage of the knowledge like to use to plan, manage, and control construction site equipment operations (Pradhananga & Teizer, 2013).

Rahimian et al. (2020) introduces, a game-like hybrid simulation that integrates BIM and machine learning for real-time monitoring of construction projects. It enhances decision-making and project management by providing actionable insights.

Application of 3D visualization and simulation techniques for tower crane operations provides insights into improving crane efficiency and safety on construction site mobilizations (Al-Hussein et al., 2006). Also Marzouk and Abubakr (2016) presents a decision-making tool for selecting tower cranes during construction integrates building information models (BIM) and genetic algorithms to optimize crane selection.

Arashpour et al. (2015) explores process integration and resource utilization in off-site construction efficiency by optimizing multi-skilled resource allocation. Also Arashpour et al. (2016) proposes a hybrid simulation approach for site layout and material laydown planning in construction projects. It considers both continuous and discrete states, aiming to enhance constructability and reduce safety risks, duration, and cost. The hybrid method combines continuous simulation (CS) and discrete event simulation (DES) to achieve more accurate decision-making (Arashpour et al., 2016). These studies contribute valuable insights about decision making in site mobilization to the field of construction engineering and management. Decision Making in site mobilization provides advantage about site equipment operations, crane location and selection, duration and cost management.

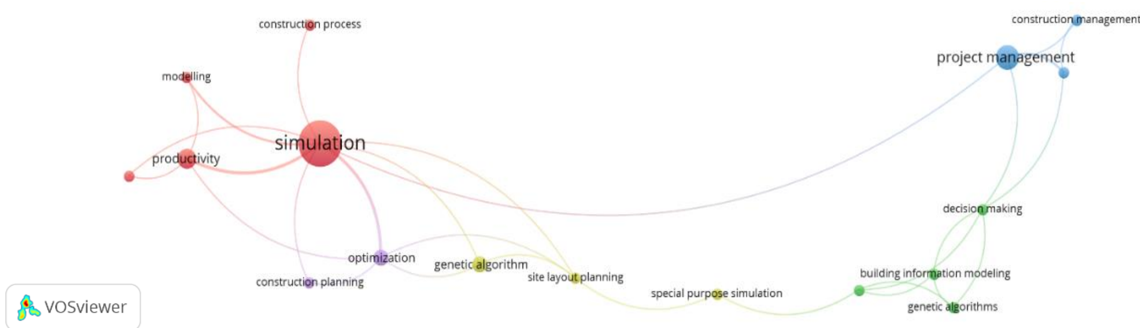

Figure 7: The bibliometric network of focused keyword “site mobilization” by VOSviewer.

Decision Making with Simulation in Construction Projects & Cost Management: The review of 15 articles obtained through literature search focuses on improving decision-making processes in cost management for construction projects. This enhancement involves innovative approaches such as cost simulation, advanced database utilization, predictive modeling for cost estimation, machine learning applications, and strategies for bidding and portfolio risk management, among other complex topics. The focus rests on the four most cited articles related to decision making in cost management.

Chou (2011) search for comprehensive stochastic processes involving the examination of a series of simulation building blocks for conceptual cost range estimates in item-based construction projects. This approach allows for a better understanding of cost dynamics and informed decision-making in construction management.

Four years later Chou and Yeh (2015) investigates to use simulation techniques for life cycle carbon dioxide emissions and environmental costs in building construction. Simulation techniques help assess the environmental impact and associated costs. Researchers developed a simulation that has CO_2 emissions evaluation system and environmental cost calculation method. This can facilitate engineers and architects decision making in evaluating primary environmental risks for building life cycles and selecting adequate construction methods (Chou & Yeh, 2015).

Cheng and Hoang (2014) proposes a new cost prediction model, namely EAC-LSPIM, assist project manager in construction cost planning and monitoring. This approach aids in calculation of more accurate cost predictions to better decision-making in project management.

This article focuses on helps decision-makers, especially project managers, to better understand cost-estimating risks in international rail construction. Study aids decision-makers, particularly project managers, in gaining a deeper comprehension of the impact of risks on costs. At an organizational level, the research enables decision-makers to sustain costs by mitigating key risks associated with cost estimation in projects. By identifying key risks, it contributes to better risk management and cost control in rail infrastructure projects (Yuan et al., 2016).

As shown Figure 8. Bibliometric network of focused keyword, these articles collectively contribute to advancing cost management practices for decision-making in construction projects by leveraging simulation and modeling techniques.

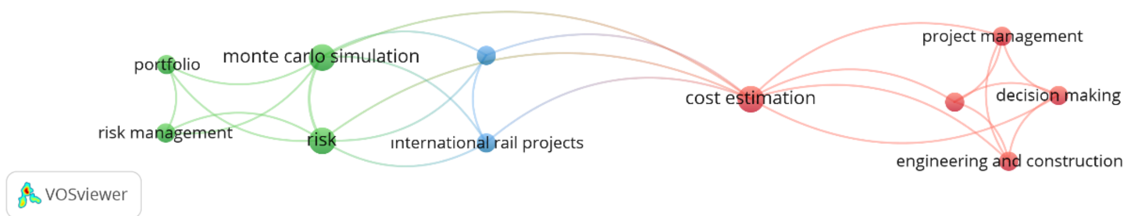

Figure 8: The bibliometric network of focused keyword "cost management" by VOSviewer.

Decision Making with Simulation in Construction Projects & Waste Management: Yazdani et al. (2021) focuses on enhancing waste collection in urban areas. Researchers proposes a new hybrid simheuristic algorithm based on an integrated simulation-optimization method about Construction and Demolition Waste Management. It employs a simheuristic approach, specifically in a case study conducted in Sydney, Australia. The results demonstrated the high performance of hybrid simulation-optimization method (Yazdani et al., 2021).

Huang et al. (2022) suggest that employing a system that integrates Building Information Modeling (BIM), Geographic Information Systems (GIS), and Internet of Things (IoT) is beneficial for managing the recycling of excavated soil. This comprehensive approach enhances coordination and monitoring throughout the soil recycling process, leading to better resource management and reduced environmental impact. By utilizing these technologies together, the system improves the accuracy of data, communication, and decision-making in soil recycling operations (Huang et al., (2022).

As shown Figure 9 bibliometric network of focused keyword, these articles collectively contribute to advancing waste management practices for decision-making in construction projects by leveraging simulation and modeling techniques espacially in last 5 years.

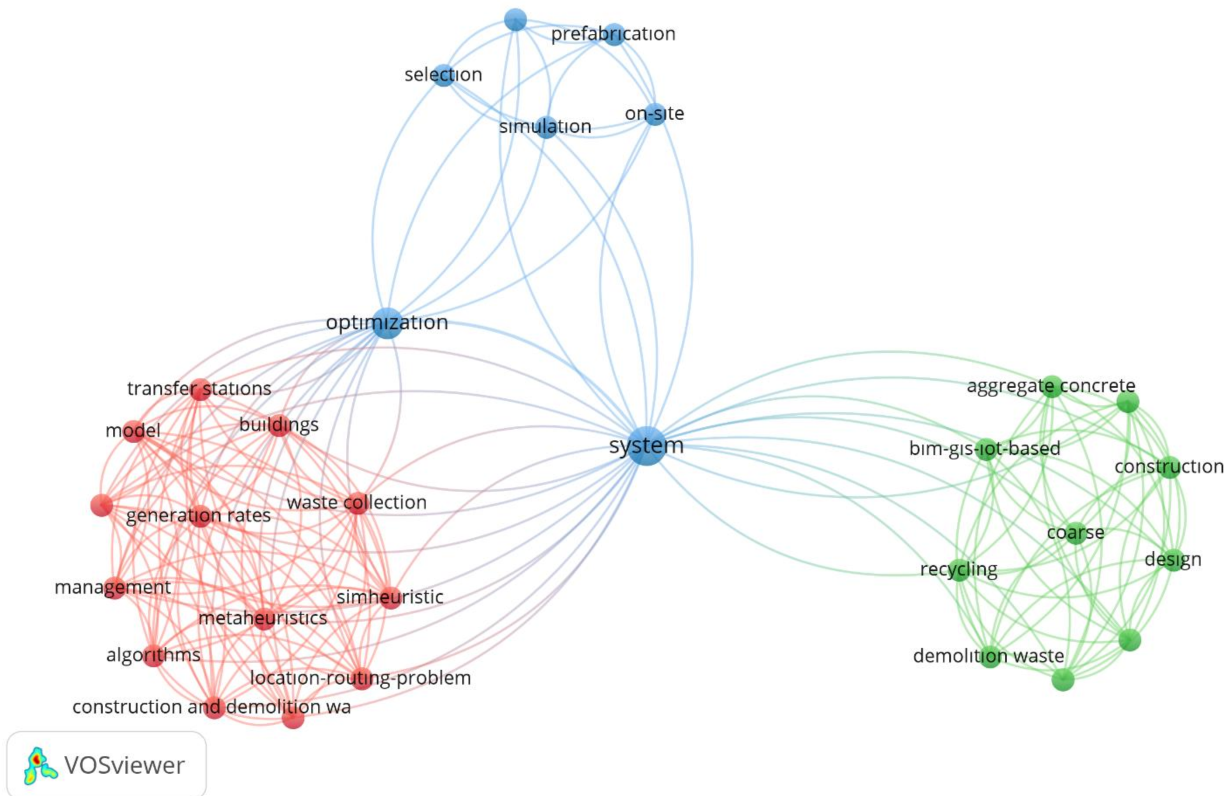

Figure 9: The bibliometric network of focused keyword "waste management" by VOSviewer.

Conclusion

The primary objective of this study is to conduct a comprehensive comparative literature review on the utilization of simulation models and tools for facilitating precise decision-making processes within construction projects under the framework of Industry 4.0. Simulation, a topic that has been explored and documented since the 1930s, encompasses a multitude of interpretations within various industrial contexts. These interpretations encompass functions such as "prediction," "decision-making," "design-modeling," "visualization," and "virtual entertainment." The inception of the Industry 4.0 concept, also referred to as the Fourth Industrial Revolution, can be traced back to the Hannover Fair in 2011, where it emerged as a pivotal element of Germany's strategic agenda aimed at bolstering the competitiveness of its manufacturing sector (Liao et al., 2017).

These simulation models and tools are used in different industries as a part of decision-making phase with the Industry 4.0 (Oliveira et al., 2016; Liao et al., 2017). In this research, the place of the use of simulation models and tools in construction projects is investigated through systemmatic literature review. During the literature review, Web of Science and Scopus databases were utilized. Using the keywords "simulation models and tools," "construction project," and "decision making" in the title/abstract/keywords domain, a collection after duplicate removal, a total of 523 papers

(N) were obtained. Subsequently, VOSviewer (2024) software was used for bibliometric search, scientometric mapping, and analysis. The bibliometric network (Figure 4) illustrating the relationships between the keywords "simulation models and tools," "construction project," and "decision making," and shows that frequently connected through four focused keywords: "risk management," "site mobilization," "cost management," and "waste management." The relationships between the identified keywords and the decision-making process in construction projects utilizing simulation models and tools were examined in detail.

In summary, decision making in construction project with simulation models and tools approach to, focusing on risk, site mobilization, cost, and waste management. In addressing keyword risk management, scholars advocate for simulation methods like fuzzy-based System Dynamic simulation to handle the dynamic nature of complex construction project risks. Emerging processes aim to tailor risk mitigation strategies to project complexities. For site mobilization, integration of advanced technologies such as GPS analysis and BIM enhances decision-making and resource allocation, boosting project efficiency. Simulation techniques play a crucial role in cost management, enabling accurate cost estimations and environmental impact assessments. In waste management, hybrid simulation-optimization methods, coupled with technologies like BIM and GIS, improve efficiency and environmental sustainability in waste collection and recycling operations. Overall, these contributions advance decision-making in construction projects by integrating simulation and modeling techniques, leading to enhanced efficiency, sustainability, and risk mitigation.

Future studies may broaden their inquiry by conducting an extensive review of the literature concerning the integration of simulation models and tools within decision-making frameworks throughout the various stages of construction projects. This expanded investigation might involve the practical application of such models and tools to representative projects, followed by an assessment of their merits and demerits. Subsequently, the dissemination of findings could encourage their wider adoption across diverse project contexts.

References

Akhavian, R., & Behzadan, A. H. (2013). Knowledge-based simulation modeling of construction fleet operations using multimodal-process data mining. *Journal of Construction Engineering and Management*, *139*(11), American Society of Civil Engineers (ASCE). https://doi.org/10.1061/(asce)co.1943-7862.0000775

Al-Hussein, M., Athar Niaz, M., Yu, H., & Kim, H. (2006). Integrating 3D visualization and simulation for tower crane operations on construction sites. *Automation in Construction*, *15*(5), 554–562. https://doi.org/10.1016/j.autcon.2005.07.007

Arashpour, M., Wakefield, R., Blismas, N., & Minas, J. (2015). Optimization of process integration and multi-skilled resource utilization in off-site construction. *Automation in Construction*, *50*, 72–80. https://doi.org/10.1016/j.autcon.2014.12.002

Arashpour, M., Wakefield, R., Lee, E. W. M., Chan, R., & Hosseini, M. R. (2016). Analysis of interacting uncertainties in on-site and off-site activities: Implications for hybrid construction. *International Journal of Project Management*, *34*(7), 1393–1402. https://doi.org/10.1016/j.ijproman.2016.02.004

Bungartz, H.-J., Zimmer, S., Buchholz, M., & Pflüger, D. (2014). Modeling and simulation. *In Springer Undergraduate Texts in Mathematics and Technology*. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-39524-6

Celen, S. (2017). Sanayi 4.0 ve simülasyon. *International Journal of 3D Printing Technologies and Digital Industry*, *1*(1), 9-26.

Cheng, M.-Y., & Hoang, N.-D. (2014). Interval estimation of construction cost at completion using least squares support vector machine. *Journal of Civil Engineering and Management*, *20*(2), 223–236). https://doi.org/10.3846/13923730.2013.801891

Chou, J.-S. (2011). Cost simulation in an item-based project involving construction engineering and management. *International Journal of Project Management*, *29*(6), 706–717. https://doi.org/10.1016/j.ijproman.2010.07.010

Chou, J.-S., & Yeh, K.-C. (2015). Life cycle carbon dioxide emissions simulation and environmental cost analysis for building construction. *Journal of Cleaner Production*, *101*, 137–147). https://doi.org/10.1016/j.jclepro.2015.04.001

Huang, T., Kou, S., Liu, D., Li, D., & Xing, F. (2022). A BIM-GIS-IoT-Based system for excavated soil recycling. *Buildings*, *12*(4), 457). MDPI AG. https://doi.org/10.3390/buildings12040457

Kuruoğlu, M., Alpyıldız, B., & Münge, U. (2000). Simulation approach in the construction sector. *2nd Construction Management Congress*, June 15-16-17, Izmir.

Landriscina, F. (2013). *Simulation and learning*. Springer New York. https://doi.org/10.1007/978-1-4614-1954-9

Liao, Y., Deschamps, F., Loures, E. de F. R., & Ramos, L. F. P. (2017). Past, present and future of Industry 4.0 - A systematic literature review and research agenda proposal. *International Journal of Production Research*, *55*(12), 3609–3629. https://doi.org/10.1080/00207543.2017.1308576

Marzouk, M., & Abubakr, A. (2016). Decision support for tower crane selection with building information models and genetic algorithms. *Automation in Construction*, *61*, 1–15. https://doi.org/10.1016/j.autcon.2015.09.008

Nasirzadeh, F., Afshar, A., Khanzadi, M., & Howick, S. (2008). Integrating system dynamics and fuzzy logic modelling for construction risk management. *Construction Management and Economics*, *26*(11), 1197–1212. https://doi.org/10.1080/01446190802459924

Oliveira, J. B., Lima, R. S., & Montevechi, J. A. B. (2016). Perspectives and relationships in supply chain simulation: A systematic literature review. *Simulation Modelling Practice and Theory*, *62*, 166–191). https://doi.org/10.1016/j.simpat.2016.02.001

de Paula Ferreira, W., Armellini, F., & De Santa-Eulalia, L. A. (2020). Simulation in industry 4.0: A state-of-the-art review. *Computers & Industrial Engineering*, *149*, 106868. https://doi.org/10.1016/j.cie.2020.106868

Rahimian, F., Seyedzadeh, S., Oliver, S., Rodriguez, S., & Dawood, N. (2020). On-demand monitoring of construction projects through a game-like hybrid application of BIM and machine learning. *Automation in Construction*, *110*, 103012. https://doi.org/10.1016/j.autcon.2019.103012

Pradhananga, N., & Teizer, J. (2013). Automatic spatio-temporal analysis of construction site equipment operations using GPS data. *Automation in Construction*, *29*, 107–122. https://doi.org/10.1016/j.autcon.2012.09.004

Qazi, A., Quigley, J., Dickson, A., & Kirytopoulos, K. (2016). Project complexity and risk management (ProCRiM): Towards modelling project complexity driven risk paths in construction projects. *International Journal of Project Management*, *34*(7), 1183–1198. https://doi.org/10.1016/j.ijproman.2016.05.008

VOSviewer (2024). Welcome to Vosviewer. https://www.vosviewer.com/. Date of Access: 19.03.2024

Wu, L., Ji, W., & AbouRizk, S. M. (2020). Bayesian inference with Markov Chain Monte Carlo–based numerical approach for input model updating. *Journal of Computing in Civil Engineering*, *34*(1). https://doi.org/10.1061/(asce)cp.1943-5487.0000862

Yazdani, M., Kabirifar, K., Frimpong, B. E., Shariati, M., Mirmozaffari, M., & Boskabadi, A. (2021). Improving construction and demolition waste collection service in an urban area using a simheuristic approach: A case study in Sydney, Australia. *Journal of Cleaner Production*, *280*, 124138. https://doi.org/10.1016/j.jclepro.2020.124138

Yuan, T., Xiang, P., Li, H., & Zhang, L. (2020). Identification of the main risks for international rail construction projects based on the effects of cost-estimating risks. *Journal of Cleaner Production*, *274*, 122904. https://doi.org/10.1016/j.jclepro.2020.122904

Zhu, Z., Jeelani, I., & Gheisari, M. (2023). Physical risk assessment of drone integration in construction using 4D simulation. *Automation in Construction*, *156*, 105099. https://doi.org/10.1016/j.autcon.2023.105099

Evaluation of Different Estimated Cost at Completion Methods Using Earned Value Management Parameters

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Abstract

In the construction industry, poor scheduling and cost control are the main factors that increase the failure of projects. Earned value management (EVM) enables the control of project cost performance and duration during the construction phase and enables the identification of changes. A limited number of studies have used actual project data for estimated cost at completion (EAC). This study focuses on; i) expressing the main parameters of EAC in cost estimation calculations for construction projects; ii) applying and evaluating the EAC methods to a completed construction project, and iii) comparing the planned progress of construction activities with the actual progress and interpreting the results. Several EAC methods from the literature were evaluated using planned and actual data of the rough activities of a real project. These methods use the actual costs and durations of the activities in the project. These EVM-based approaches for estimating the cost of construction projects are expected to assist project managers in cost estimation. Furthermore, it is considered that the study will contribute to a better understanding of the EVM approach.

Keywords: *construction industry, earned value management, estimated cost at completion.*

Introduction

Since project management is concerned with decisions that affect the future, time and cost estimates are crucial for the correct management and success of projects in general (Batselier & Vanhoucke, 2015). Earned value management (EVM) integrates scope, cost, and schedule control under the same framework to assess project performance and progress (PMBOK, 2013). This management technique generates performance indices and variances that allow managers to determine excessive costs and delays (Pajares, 2011). Estimating the final cost of the project is crucial to the success/failure of a project, as it provides an opportunity to take corrective measures when the estimated EAC (₺) surpasses a specific threshold (Vanhoucke, 2016).

The pioneering study comparing the accuracy of EAC methods was developed by Zwikael et al. (2000). They discussed how to estimate the final cost of a project and evaluated the performance of five forecasting models with data obtained from a sample of real projects. Three measures of forecast performance; mean squared error (MSE), mean absolute deviation (MAD), and mean absolute percentage error (MAPE) were used to evaluate the performances of the established five models. Batselier and Vanhoucke (2015) on the other hand compared the accuracy of Methods 1–8 in Table 1 on a database of 51 real-life projects (39 of which were construction projects). They evaluated the accuracy of the methods with MAPE and concluded that methods 1, 2, and 8 were the most accurate. Vanhoucke (2016) made a comparison of EAC (₺) based cost methods. He compared the methods between 1 and 8 as presented in Table 1. He considered the mean absolute performance errors (MAPE) and concluded that method 6 is the most accurate. Currently, Barrientos-Orellana et al. (2023) compared the stability and accuracy of 30 cost estimation methods in EVM. They evaluated the accuracy of EAC (₺) methods with MSE, mean percentage error (MPE), and MAPE. They concluded that the general results of Method 1 in Table 1 are higher than the others. The tracking periods of the previous studies were determined as durations representing 10% of the actual duration, tracking in the form of classification of the percentage of completion based on early, middle, and late stages, and weekly tracking. The researchers made comparisons of the estimation methods using these tracking periods. However, the subject of the accuracy of EAC cost estimation methods based on the daily tracking of a real construction project has not been adequately addressed. Therefore, in this study, the evaluation of the cost estimation results obtained based on EVM in the case of using “day” as the tracking period was carried out.

Material and Method

Establishment of Cost Estimation Methods

Initially, information related to the basic parameters and performance metrics of EVM was provided. As a case study, the planned and actual time and cost data of the rough works of a housing project, consisting of four floors and twelve flats, were used. The actual completion time of the project was 122 days, and the project process was monitored daily throughout the 122 days. Within the scope of the study, the cost estimation methods between 1 and 8 in Table 1 were applied to the housing project data, and the method performances were evaluated via mean percentage error (MPE) and mean absolute percentage error (MAPE) criteria.

Table 1. Established cost estimation methods.

ID	Mathematical Equation	Explanation
1	$EAC_{PV1} = AC + (BAC - EV)$	The methods 1–5 (Christensen, 1999) consider PF=1, CPI, SPI, SCI=SPI*CPI, and weighted time/cost performance. For cost estimation, **α = 0.8** and **β = 0.2** as the cost performance index (CPI) should significantly outweigh the schedule performance index (SPI).
2	$EAC_{PV2} = AC + (BAC - EV)/CPI$	
3	$EAC_{PV3} = AC + (BAC - EV)/SPI$	
4	$EAC_{PV4} = AC + (BAC - EV)/SCI$	
5	$EAC_{PV5} = AC + (BAC - EV)/(\boldsymbol{\alpha}\, CPI+\boldsymbol{\beta}\, SPI)$	
6	$EAC_{ES1} = AC + (BAC - EV) /SPI(t)$	The methods 6–8 (Lipke, 2003; Barrientos-Orellana et al., 2023) consider PF = SPI(t), SCI(t), and weighted time/cost performance. For method 8, **α = 0.8** and **β = 0.2**.
7	$EAC_{ES2} = AC + (BAC - EV) /SCI(t)$	
8	$EAC_{ES3} = AC + (BAC - EV) /\boldsymbol{\alpha}\, CPI+\boldsymbol{\beta}\, SPI(t)$	

Earned Value Key Parameters

EVM requires three key parameters to monitor the performance of a project, including planned value (PV), earned value (EV), and actual cost (AC). PV is usually referred to as budgeted cost of work scheduled (BCWS), (Vanhoucke, 2016). The authorized budget is planned to carry out the work to be completed for an activity or work breakdown structure component, however, the mentioned budget does not include the management reserve. The total value planned for the project is also referred to as the budget at completion (BAC), (PMBOK, 2013). EV represents the amount budgeted for the implementation of the work completed by a given status date. It is called the Budgeted Cost of Work Performed (BCWP). EV is equal to the percentage of activity/project completion at a given time multiplied by the total activity/project budget at that time (Vanhoucke, 2016). AC represents the monetary value expended to achieve the progress made at a given point in time (Khamooshi & Golafshani, 2014). It is also known as the Actual Cost of Work Performed (ACWP). Earned schedule (ES) is stated to be a fourth key parameter, based on planned value and earned value. ES refers to the conversion of the current earned value (EV at actual time-AT) into time units by determining when it should be earned in the baseline schedule (Vanhoucke, 2016).

Earned Value Performance Metrics

EVM provides a variety of performance metrics designed to assist in project monitoring and control; these metrics vary according to the type of information needed (Khamooshi & Golafshani, 2014). These metrics are defined as follows:

The cost variance (CV) refers to the budget deficit or surplus at a given point in time. It is defined as the difference between the earned value and the actual cost (PMBOK, 2013). The cost performance index (CPI) is a measure that expresses the current cost performance of the project and indicates whether the project cost is under budget, on budget, or over budget. Mathematically, it is calculated with the formula CPI=EV/AC (Vanhoucke, 2016). The CPI metric of less than one indicates that the productivity of the utilization of the resources allocated to the project is not good. If this metric is equal to one, it is concluded that the value obtained is exactly equal to the actual cost and the conditions are favorable. If the CPI is greater than one, this indicates that the productivity of the use of resources allocated to the project is good (Damavandi et al., 2024).

The schedule variance (SV) is defined as the difference between the earned value and the planned value (PMBOK, 2013). The schedule performance index, which depends on whether EV or ES is used, is abbreviated as SPI or SPI(t). A measure that expresses the current time performance of the project and indicates whether the project is ahead of schedule, on time, or delayed. It is mathematically calculated with the formulas SPI=EV/PV and SPI(t)=ES/AT (Vanhoucke, 2016). The SPI metric of less than one indicates that the productivity of the project team in utilizing the time allocated to the project is low. If this metric is equal to one, it is concluded that the value obtained is equal to the planned value and the conditions are good. If the SPI metric is greater than one, it indicates that the productivity of the project team in utilizing the time allocated to the project is high (Damavandi et al., 2024).

Validation of Cost Estimation Methods

The performance of the estimation methods was evaluated based on statistical indicators such as mean percentage error (MPE) and mean absolute percentage error (MAPE). The MPE, defined as Equation 1 is a general measure of estimation deviations and is a calculated average of the percentage errors (Quej et al., 2016). Average percentage errors between -10% and +10% are considered acceptable (Kirmani et al., 2015). MPE calculations can take a positive or negative value. If the MPE value is positive, this indicates that the estimated value is higher than the actual value, and means that there is an overestimation. If the MPE value is negative, this indicates that the estimated value is lower than the actual value, and means that there is an underestimation (Winebrake & Sakya, 2006). The fact that the MPE value has an average value close to zero does not mean that a near-perfect estimation is performed. In MPE, the mean can be close to zero, but positive and negative forecasts can balance each other (Winebrake & Sakya, 2006; Barthwal & Acharya, 2021). Therefore, MAPE, defined in Equation 2, was also used as an evaluation criterion. The MPE results in Table 2 show the deviations of the estimation methods.

MAPE is a general measure of estimation accuracy and is calculated from the absolute differences between a set of estimated and calculated data (Quej et al., 2016). It is one of the most popular error measurements because it is percentage-based, and the value should be as close to zero as possible (Zeiml et al., 2019). Bayram and Çıtakoğlu (2023) stated that if the MAPE criterion is below 10%, the estimates are “high”; if it is between 10% and 20%, it is “good”; if it is between 20% and 50%, it is “reasonable”; and if it is greater than 50%, it is “inaccurate.” The mathematical equations for MPE and MAPE are presented below.

$$\text{MPE (\%)} = \left[\frac{1}{T}\sum_{t=1}^{T}\frac{EAC(₺)-\text{RC})}{RC}\right] \quad (1)$$

$$\text{MAPE (\%)} = \left[\frac{1}{T}\sum_{t=1}^{T}\frac{|EAC(₺)-\text{RC}|)}{RC}\right] \quad (2)$$

Where; *T* is the number of periodic monitoring periods, *EAC (₺)* is the cost estimate for each periodic monitoring period, and *RC* is the actual cost.

Findings

The data of a real-life housing project; including basic information for the application of EVM-related methods, project start date, work breakdown structure (WBS), resources for activities, and a daily report, were used for the application. The estimation accuracies of eight EAC (₺) cost estimation methods were evaluated via collected data. The measurement of the accuracy of an EAC (₺) method was performed through two error types; MPE and MAPE as aforementioned. The EVM basic parameters of the project are presented in Figure 1. As can be seen from Figure 1, the project was completed early and faced budget overruns.

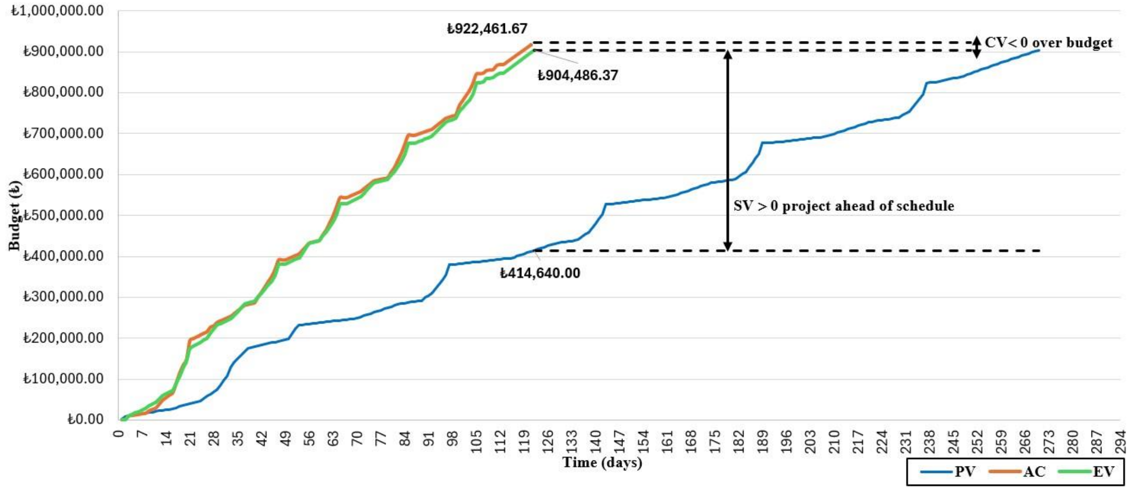

Figure 1: EVM key metrics for the case project.

The dashboard shows the schedule performance (SPI or SPI(t)) on the x-axis and the cost performance (CPI) on the y-axis. Figure 2 shows the evolution of the project from start to finish in the EVM schedule/cost dashboard evaluated with SPI and CPI.

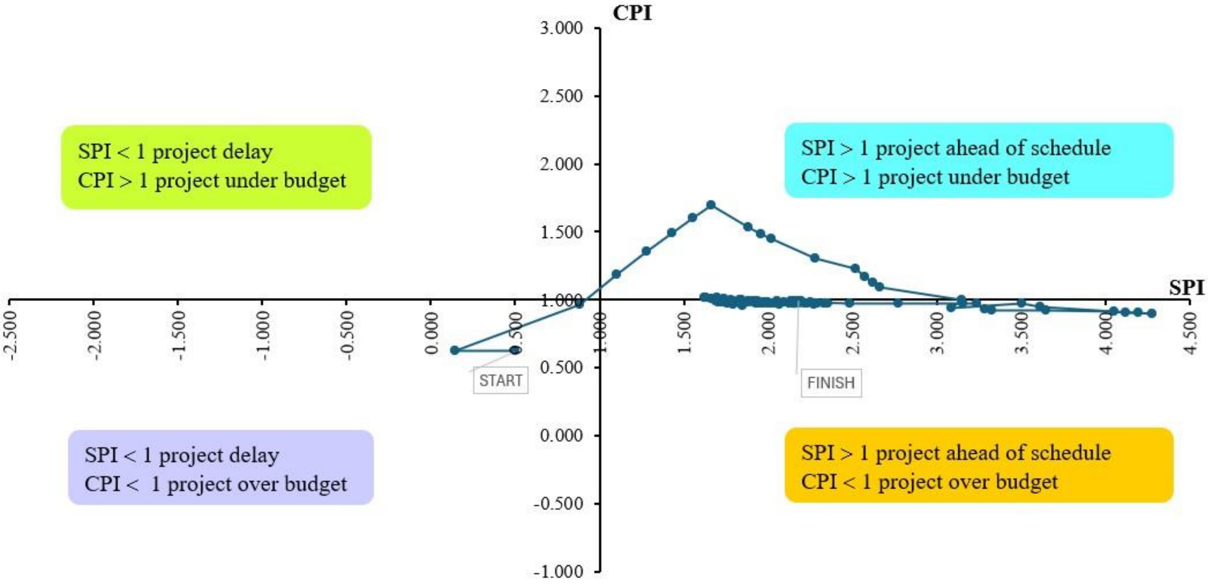

Figure 2: EVM schedule/cost performance dashboard and SPI/CPI dashboard for the project.

In the first three days of the construction, both SPI and CPI performance metrics were determined to be less than one. This situation indicates that a delay occurred in the schedule and that the project was facing the problem of a budget overrun. In the examinations between the 3rd and 17th days, and the 35th and 42nd days, it was determined that both SPI and CPI performance metrics were greater than one. This finding indicates that the project is ahead of schedule and under budget. In the examinations between the 16th and 36th days, and the 41st and 122nd days, it was determined that the SPI metric was greater than one but the CPI metric was less than one. This finding reflects that the project was ahead of schedule but over budget. Figure 3 shows the evolution of the project from start to finish in the EVM schedule/cost dashboard evaluated with SPI(t) and CPI.

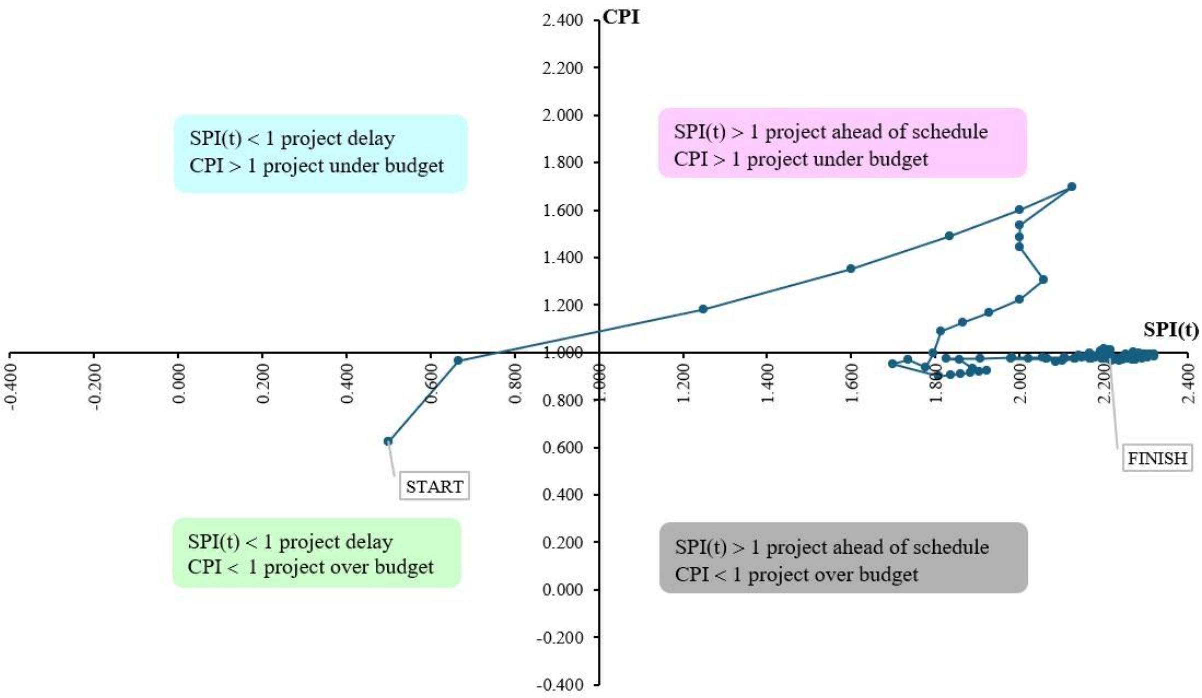

Figure 3: EVM time/cost performance dashboard and SPI(t)/CPI dashboard for the project.

Figure 3 presents that in a general evaluation of the project, it was observed that the majority of the periodic monitoring days are concentrated in the area where SPI(t) is greater than one but CPI is less than one. This finding indicates that the project was completed ahead of schedule and faced a budget overrun.

The aforementioned performance indicators finally were calculated to determine whether the results of the estimation methods deviated significantly from the calculated data. The smaller MPE and MAPE values indicated a better approximation to the calculated data. The results of MPE and MAPE performance criteria calculated for each EAC (₺) estimation method are presented in Table 2. Furthermore, the MAPE values of eight cost estimation methods are also presented in Figure 4. The MPE values range from -21.931 to -0.930. The MPE values of the EAC_{PV1} and EAC_{PV2} methods were determined to be closest to zero. This situation showed that the values estimated by the mentioned methods are close to the actual values. The MAPE values of the EAC (₺) estimation methods on the other hand range from 1.06 to 35.48. In this study, the success level of cost estimation methods is evaluated based on the MAPE performance criterion stated by Bayram and Citakoglu (2023). The MAPE values of the EAC_{PV1} and EAC_{PV2} estimation methods are below 10% and have a high level of estimation accuracy. The MAPE values of the EAC_{PV5} and EAC_{ES3} estimation methods are between 10% and 20% and have a good level of estimation accuracy. The MAPE values of the EAC_{PV3}, EAC_{PV4}, EAC_{ES1}, and EAC_{ES2} estimation methods are between 20% and 50% and have a reasonable level of estimation accuracy.

Table 2. MPE and MAPE values for the eight EAC (ȶ) estimation methods.

Cost Estimation Methods	Performance Criteria		Cost Estimation Methods	Performance Criteria	
	MPE (%)	MAPE (%)		MPE (%)	MAPE (%)
EAC_{PV1}	**-0.930**	**1.055**	**EAC_{PV5}**	**-9.651**	**12.166**
EAC_{PV2}	**-1.433**	**4.965**	**EAC_{ES1}**	-21.931	25.845
EAC_{PV3}	-19.060	30.076	**EAC_{ES2}**	-20.752	28.656
EAC_{PV4}	-15.817	35.478	**EAC_{ES3}**	**-8.662**	**10.898**

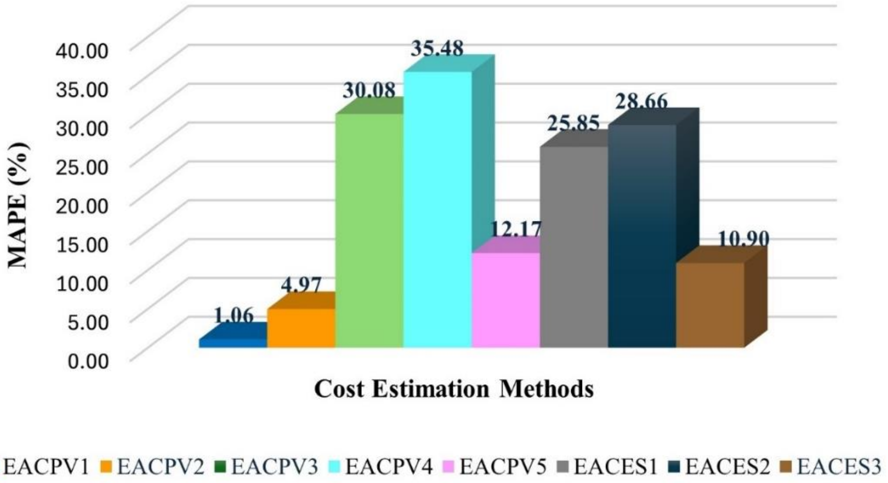

Figure 4: MAPE values of the eight EAC (ȶ) estimation methods with tracking period unit in days.

Discussion and Conclusion

One of the most significant objectives of construction project management is to complete the projects in line with the approved budget and schedule. Previous studies reveal that cost estimation is always a popular and considerable issue. Within the scope of this study, two different performance criteria were evaluated. The results confirm that MPE and MAPE in general are consistent with each other. The MAPE performance criteria was previously used in similar studies (Zwikael et al., 2000; Batselier & Vanhoucke, 2015; Vanhoucke, 2016; Barrientos-Orellana et al., 2023).

The success order of the eight EAC (ȶ) cost estimation methods was obtained as follows: EAC_{PV1} > EAC_{PV2} > EAC_{ES3} > EAC_{PV5} > EAC_{ES1} > EAC_{ES2} > EAC_{PV3} > EAC_{PV4}. EAC_{PV1} and EAC_{PV2} are found as the outperforming methods. EAC_{ES3} and EAC_{PV5} also performed well. The EAC_{PV1} method (equal to AC + (BAC - EV)/PF) was the top in terms of MAPE. Barrientos-Orellana et al. (2023) also reported a similar finding. Therefore, the method with a performance factor equal to one showed higher accuracy than the other methods. This finding is in line with the inferences made by Yang et al. (2023) regarding the performance factor. Yang et al. (2023) emphasized that if the performance factor is one, the project is expected to work as planned, and the importance of this factor being equal to one for construction projects is also confirmed.

This research concluded that EVM can be used as an effective tool in evaluating construction project progress and cost performance. Although it is quite difficult to conduct academic studies with data obtained directly from the construction sites in Türkiye, this study considers a housing project. The two different project scenarios, for example, a project finished on time and a project delayed, with different physical characteristics and/or usage purposes can also be adapted to extend the scope of this study. In addition, the current body of knowledge indicates that further case studies are required to assess the impact of different construction projects on the performance of earned value methods.

References

Barrientos-Orellana, A., Ballesteros-Pérez, P., Mora-Melià, D., Cerezo-Narváez, A., & Gutiérrez-Bahamondes, J. H. (2023). Comparison of the stability and accuracy of deterministic project cost prediction methods in earned value management. *Buildings*, *13*(5), 1206.

Barthwal, A., & Acharya, D. (2021). An IoT based sensing system for modeling and forecasting urban air quality. *Wireless Personal Communications*, *116*(4), 3503-3526.

Batselier, J., & Vanhoucke, M. (2015). Empirical evaluation of earned value management forecasting accuracy for time and cost. *Journal of Construction Engineering and Management*, *141*(11), 05015010.

Bayram, S., & Çıtakoğlu, H. (2023). Modeling monthly reference evapotranspiration process in Turkey: application of machine learning methods. *Environmental Monitoring and Assessment*, *195*(1), 67.

Christensen, D. S. (1999). Value cost management report to evaluate the contractor's estimate at completion. *Acquisition Review Quarterly*, *283*, 295.

Damavandi, M., Tavakoli, M., & Jolai, F. (2024). Project cost forecasting based on earned value management and Markov chain. *Annals of Operations Research*, 1-26.

Khamooshi, H., & Golafshani, H. (2014). EDM: Earned Duration Management, a new approach to schedule performance management and measurement. *International Journal of Project Management*, *32*(6), 1019-1041.

Kirmani, S., Jamil, M., & Rizwan, M. (2015). Empirical correlation of estimating global solar radiation using meteorological parameters. *International Journal of Sustainable Energy*, *34*(5), 327-339.

Lipke, W. (2003). Schedule is different. *The Measurable News*, *31*(4), 31-34.

Pajares, J., & Lopez-Paredes, A. (2011). An extension of the EVM analysis for project monitoring: The cost control index and the schedule control index. *International Journal of Project Management*, *29*(5), 615-621.

PMBOK® A Guide to the Project Management Body of Knowledge (5^{th} edition). (2013). Project Management Institute Inc, Pennsylvania, ABD.

Quej, V. H., Almorox, J., Ibrakhimov, M., & Saito, L. (2016). Empirical models for estimating daily global solar radiation in Yucatán Peninsula, Mexico. *Energy Conversion and Management*, *110*, 448-456.

Vanhoucke, M. (2016). *Integrated project management sourcebook : A technical guide to project scheduling, risk and control*. Springer International Publishing, Switzerland.

Winebrake, J. J., & Sakva, D. (2006). An evaluation of errors in US energy forecasts: 1982–2003. *Energy Policy*, *34*(18), 3475-3483.

Yang, J. B., & Lai, T. H. (2023). Selecting EVM, ESM and EDM (t) for managing construction project schedule. *Engineering, Construction and Architectural Management*.

Zeiml, S., Altendorfer, K., Felberbauer, T., & Nurgazina, J. (2019). Simulation based forecast data generation and evaluation of forecast error measures. In *2019 Winter Simulation Conference (WSC)* (pp. 2119-2130). IEEE.

Zwikael, O., Globerson, S., & Raz, T. (2000). Evaluation of models for forecasting the final cost of a project. *Project Management Journal*, *31*(1), 53-57.

Quantifying the Combined Effects of Time, Cost, and Quality Control on Project Delivery in Nigeria: The Lagos Construction Industry Case

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Abstract

The Nigerian construction industry has experienced several obstacles, resulting in slow, stagnant, and ultimately abandoned project outcomes. While some studies on construction project management (CPM) have identified factors such as time, quality, and cost as having a substantial impact on project delivery in Nigeria, some have had limitations in methodology. This paper examined the effect of time, quality, and cost on project delivery in Lagos, Nigeria. Using a quantitative methodology, data was collected via questionnaire ($n = 150$) and evaluated quantitatively. The study found a significant correlation between project delivery time ($r = .645^*$, $p<.05$), quality ($r = .599$, $p<.05$), and cost ($r = .528^*$, $p<.05$), as well as the joint and relative effect of time, quality, and cost on project delivery ($f(3/146) = 173.254$, $p > 0.05$). The most significant predictors were quality ($\beta = 0.594$, $t = 15.310$, $p < 0.05$), time ($\beta = 0.563$, $t = 10.492$, $p < 0.05$), and cost ($\beta = 0.118$, $t = 2.198$, $p < 0.05$). The study advocated that construction sector stakeholders put novel monitoring and evaluation (M&E) techniques into practice. It concluded that traditional M&E must be replaced by the current approach of using M&E software for CPM in Lagos, Nigeria.

Keywords: *construction industry, construction project management, project delivery, Nigeria.*

Introduction

The construction industry in Nigeria faces significant challenges, including funding shortages, corruption, inadequate project management, and deficient infrastructure. These obstacles hinder the efficient delivery of construction projects, affecting their quality and timeliness. Successful project delivery in this sector requires meticulous resource management, considering time, cost, and quality, as highlighted by Hussain et al. (2024). However, due to its complexity and involvement of various stakeholders, including owners, contractors, architects, engineers, suppliers, and regulatory bodies, the construction industry remains one of the most intricate sectors for project management (Eskerod et al., 2015). In this context, project managers must delicately balance adhering to budget constraints with meeting stringent quality and time targets. Inaccurate cost estimations can lead to cost overruns, endangering profit margins and project feasibility (Robles, 2023). Meanwhile, effective quality management requires rigorous quality control measures and continuous inspections throughout all project phases, as emphasized by Muhammad (2021).

In Nigeria, infrastructure development often faces challenges such as cost escalations, delays, and substandard quality due to factors like corruption, inadequate funding, and poor project management practices. These challenges not only hinder project completion but also have adverse effects on the economy and citizens' well-being. Given this context, it is essential to examine the impact of cost, quality, and time on project delivery specifically in Lagos, Nigeria, and identify factors influencing project delivery to offer actionable recommendations for improvement. The study aims to analyze the effect of cost, quality, and time on project delivery, identify influential factors, assess the effectiveness of project management practices, and provide recommendations for enhancement. To guide empirical analysis, hypotheses were formulated as follows:

Hypothesis 1: There is a significant relationship between time and project delivery in Lagos, Nigerian construction industry
Hypothesis 2: There is a significant relationship between cost and project delivery in Lagos, Nigerian construction industry
Hypothesis 3: There is a significant relationship between quality and project delivery in Lagos, Nigerian construction industry
Hypothesis 4: There is a significant joint and relative effect of time, quality and cost on project delivery in Lagos, Nigerian construction industry

Literature Review

The Nigerian construction industry faces numerous challenges that significantly impact project delivery, including delays, cost overruns, and compromised quality. Extensive literature reviews shed light on the effects of time, quality, and cost on project delivery within this context. Festus (2021) found that time overruns affect approximately 35% of construction projects in Nigeria. Omopariola (2021) identified factors contributing to time delays, including deficient project planning, inadequate skilled personnel, communication breakdowns, and funding shortages. Government bureaucracy, political instability, and security concerns further exacerbate these delays. According to Hamid et al. (2023) time delays not only hinder project completion but also escalate costs, spawn legal disputes, and strain client relationships. Quality is another critical aspect suffering in the Nigerian construction industry, leading to rework, project extensions, and financial setbacks. Meanwhile, Mamman and Umesi (2022) identified substandard materials, insufficient supervision, and poor workmanship as compounding factors. Hence, as posited by Godwin (2023) the absence of robust quality management systems exacerbates quality concerns. Ogbu and Ehigiator-Irughe (2020) expressed concern about cost overruns which represent a significant challenge, with inadequate cost control measures and subpar project planning being primary culprits. In addressing these challenges, Abdullahi et al. (2019) posited that quality management systems have emerged as focal points within the industry, aiming to standardize processes, minimize waste, and enhance profit margins. Meanwhile, Osegbo et al. (2021) suggest that formal quality management systems can mitigate errors and ensure consistent delivery of goods and services. Although international quality management standards like ISO 9000 have gained recognition in Nigeria, challenges persist in their implementation (Achi et al., 2007). The current study aims to assess quality management practices and identify factors hindering their adoption in the Nigerian construction sector. Consistent quality assurance relies on a documented quality management system integrating control, assurance, and improvement processes.

Research Methodology

This study employed a quantitative research approach and utilized a survey questionnaire to gather data from an extensive sample comprising civil engineers, construction professionals, contractors, and project owners. The study was conducted in Lagos, Nigeria (Figure 1), located in the southwest region of Africa, bordered by the Gulf of Guinea and Benin. Lagos is Nigeria's largest city and is renowned as Africa's most populous urban center. It is situated at coordinates latitude 6.45407 and longitude 3.39467, falling within the northern hemisphere. Geographically, Lagos is nestled along the south western coastline of Nigeria, adjacent to the Niger River delta, making it strategically positioned on the Atlantic coast within the Gulf of Guinea (Figure 2). The authors developed a structured questionnaire titled 'Effect of Time, Cost, and Quality Control on Project Delivery Questionnaire (TCQCPDQ)'. The questionnaire consisted of five sections labelled A through E.

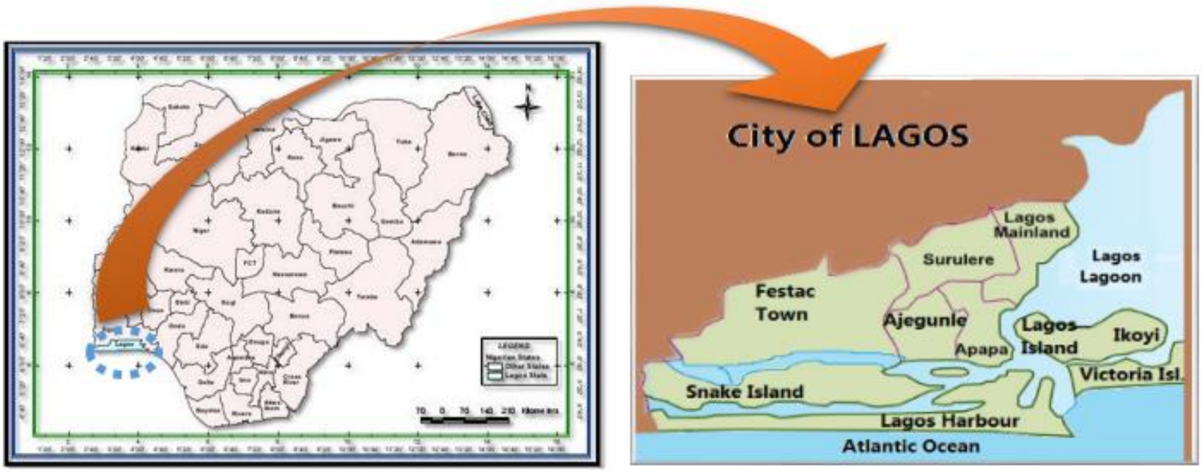

Figure 1: Map of Nigeria showing Lagos State   Figure 2: Map of Nigeria showing Lagos State
Source: Adeniyi et al. (2016).

Section A gathered respondents' demographic information such as age, gender, religion, marital status, and education level. Sections B, C, D, and E each contained twelve items drawn from the Time Control Scales (TCS), Cost Control Scales (CCS). Quality Control Scales (QCS) and Project Delivery Scales (PDS) respectively. Participants were instructed to rate their agreement with each item using a 4-point Likert-type scale, with responses ranging from 'Strongly Disagree' (1) to 'Strongly Agree' (4). To establish content validity, expert opinions, literature reviews, and pretesting of closed-ended questions were conducted. In line with Uwakwe's (2017) definition of reliability as the consistency of obtaining similar results upon repeated administration over time, a draft of the questionnaire was subjected to expert critique to ensure reliability. The reliability of the instruments was assessed using Cronbach's alpha.

The questionnaire used for data collection primarily comprised closed-ended questions tailored to elicit information on the interplay between time, quality, and cost in project delivery within Lagos, Nigeria. To define the list of factors influencing project delivery time in Lagos, the authors selected and classified the many aspects that can influence the duration and efficiency of completing construction projects in the research area based on literature and professional practice. A structured strategy was taken to define such a list. This included (i) stakeholder engagement and management; (ii) environmental and infrastructure considerations; (iii) resource management; (iv) project planning and execution; (v) legal and contractual issues; (vi) market dynamics; and (vii) geopolitical and social factors. Thus, by completely describing these elements, the authors had a better understanding of the issues specific to Lagos building projects and would be able to mitigate risks, optimise project schedules, and improve overall project delivery performance. Following these approach of defining the list, the study used a sample size of 200 respondents, with 150 filling out and returning surveys, resulting in a 75% response rate. This response rate was excellent and representative enough to draw inferences from the study. The gathered data was analysed using SPSS version 20 and Ms Excel computer programmes, then summarised using descriptive statistics and displayed in tables and graphs, frequency count, percentages, Pearson Product Moment Correlation (PPMC), and regression analysis to unveil insights into the research objectives. The hypotheses were evaluated using a 95% confidence interval.

Result and Findings

The findings of the study provide insights into the demographic characteristics of the participants. The majority of respondents were engineers (35.2%), then architects (20.5%), quantity surveyors (14.7%), and contractors (17.6%). Regarding gender distribution, there was a predominance of male respondents (64.0%) while females made up 36.0%. In terms of age, a significant proportion fell within the 25-30 age bracket (44.0%), followed by those aged 31-35 (54.0%), indicating a youthful cohort of professionals. Regarding educational background, the majority held HND/degree qualifications (53.3%), followed by NCE/ND education (46.0%), with less than 1% possessing Master's degrees, suggesting a generally high level of education among respondents. In terms of professional experience, the majority were highly experienced professionals, with 56.7% having over 20 years of experience. In terms of project involvement, a significant portion of respondents had extensive project experience, with 56.7% having handled over 20 projects. Overall, these demographic characteristics indicate a diverse and experienced group of professionals capable of providing valuable insights for the study.

To investigate the factors influencing project delivery time, data was collected to address the research question: "What are the factors affecting project delivery time in Lagos State, Nigeria?" Analysis of the data, as shown in Table 1, revealed thirteen factors with mean scores surpassing the criterion mean of 2.50, indicating agreement among respondents on their significance.

"Delay in work approval" was the top-ranked factor with a mean score of 3.529, followed by "Delay in inspection and testing of work" with a mean score of 3.471. "Shortage of construction materials" ranked third with a mean score of 3.353, while "Deficiencies in organization and design change" shared the fourth position with a mean score of 3.294. These findings collectively highlight the primary factors influencing project delivery time in Lagos, Nigeria.

Table 1. Factors affecting time of project delivery in Lagos, Nigeria.

S/N	Factors Affecting Time	Weighted Sum	Mean Score	RII	Rank
1	Planning and scheduling deficiencies	101	2.971	0.743	10th
2	Labour shortage	108	3.176	0.794	6th
3	Design change	112	3.294	0.824	4th
4	Slow decision making	101	2.971	0.743	10th
5	Delay in work approval	120	3.529	0.882	1st
6	Waiting for information	86	2.529	0.632	13th
7	Delay in inspection and testing of work	118	3.471	0.868	2nd
8	Deficiencies in organization	112	3.294	0.824	4th
9	Incomplete drawings	106	3.118	0.779	8th
10	Insufficient number of equipment	108	3.176	0.794	6th
11	Shortage of construction material	114	3.353	0.838	3rd
12	Problem with neigbhours	106	3.118	0.779	8th
13	Late delivery	100	2.941	0.735	12th

To ascertain whether a correlation exists between time and project delivery, Hypothesis 1 was examined, positing a significant relationship between these variables. Analysis presented in Table 2 indicates a noteworthy positive correlation between time and project delivery (r = .645**, N = 150, p < .05). This outcome rejects the null hypothesis and validates the alternate hypothesis, affirming the presence of a significant relationship between time and project delivery.

Table 2. Relationship between time and project delivery in Lagos, Nigeria industry.

Variable	Mean	Std. Dev.	N	R	P	Remark
Project delivery	31.53	5.58				
			150	.645**	.000	Sig.
Time factors	41.86	9.36				

*Sig. at .05 level

To identify the factors influencing cost management in the construction industry, data was gathered to address the research question regarding the factors affecting cost management. Table 3 illustrates that out of the 13 items assessed, five items garnered mean scores exceeding the criterion mean of 2.50, indicating consensus among respondents regarding their impact on cost management. These factors, ranked by their mean scores, include Escalation of materials prices (3.441 > 2.50), Monthly payment difficulties (3.353 > 2.50), Financing and payment completed work and Deficiencies in cost estimates (3.324 > 2.50), Weather (3.235 > 2.50), and Change in site conditions (3.176 > 2.50).

Furthermore, to investigate the relationship between cost and project delivery, Hypothesis 2 was tested, proposing a significant relationship between these variables. Analysis presented in Table 4 reveals a notable positive correlation between cost and project delivery (r = .528**, N = 150, p < .05). This finding rejects the null hypothesis and confirms the alternate hypothesis, affirming the presence of a significant relationship between cost and project delivery.

Table 3. Factors affecting cost management in construction industry in Lagos States, Nigeria.

S/N	Factors Affecting Cost	Weighted Sum	Mean Score	RII	Rank
1	Fraudulent practice & kickbacks	97	2.853	0.713	10th
2	Poor contract management	102	3.000	0.750	8th
3	Mistakes and discrepancies in contract document	92	2.706	0.676	11th
4	Deficiencies in cost estimates	113	3.324	0.831	3rd
5	Changes in design	104	3.058	0.765	7th
6	Construction methods	98	2.882	0.721	9th
7	Escalation of materials prices	117	3.441	0.860	1st
8	Change in site conditions	108	3.176	0.794	6th
9	Labour and management relation	72	2.118	0.529	13th
10	Financing and payment completed work	113	3.324	0.831	3rd
11	Monthly payment difficulties	114	3.353	0.838	2nd
12	Weather	110	3.235	0.809	5th
13	Shortage of material	88	2.588	0.647	12th

Table 4. Relationship between cost and project delivery in Lagos, Nigeria.

Variable	Mean	Std. Dev.	N	R	P	Remark
Project delivery	31.53	5.58	150	.528**	.000	Sig.
Cost factors	41.25	6.22				

*Sig. at .05 level

To comprehend the factors influencing quality management in project delivery within the construction industry, data was collected to address the research inquiry regarding the most effective quality management practices. Table 5 presents the mean ranking of five items, indicating consensus among respondents on their effectiveness in quality management.

Table 5. Factors affecting quality management in construction industry in Lagos, Nigeria.

S/N	Factors Affecting Quality	Weighted Sum	Mean Score	RII	Rank
1	Absence of clear uniform evaluation standard	105	3.088	0.772	7th
2	Inadequate control procedure	117	3.441	0.860	1st
3	Deficiencies in coordination	83	2.441	0.610	14th
4	Material management problem	101	2.971	0.743	9th
5	Mistake during constructions	106	3.118	0.779	6th
6	Designers ignorance about client requirement	88	2.588	0.647	12th
7	Non adherence to contract condition	105	3.088	0.772	7th
8	Frequent equipment breakdown	107	3.147	0.787	4th
9	Ineffective communication	96	2.824	0.706	11th
10	Incomplete drawings	107	3.147	0.787	4th
11	Shortage of technical personnel	115	3.382	0.846	2nd
12	Weather	100	2.941	0.735	10th
13	Confined site	84	2.471	0.618	13th
14	Unexpected geological condition	114	3.353	0.838	3rd

The items, ranked by their mean scores, include Material management problem (3.67 > 2.50), Inadequate control procedure (3.57 > 2.50), Frequent equipment breakdown (3.52 > 2.50), Deficiencies in coordination (3.50 > 2.50), and Non-adherence to contract conditions (3.46 > 2.50). Moreover, to explore the relationship between quality and project delivery, Hypothesis 3 was tested, proposing a significant relationship between these variables. As depicted in Table 6, a noteworthy positive correlation between quality and project delivery is evident ($r = .599^{**}$, $N = 150$, $p < .05$). This outcome rejects the null hypothesis and validates the alternate hypothesis, affirming the presence of a significant relationship between quality and project delivery in the Lagos, Nigerian construction industry.

Table 6. Relationship between quality and project delivery in Lagos, Nigeria industry.

Variable	Mean	Std. Dev.	N	R	P	Remark
Project delivery	31.53	5.58				
			150	.599**	.000	Sig.
Quality factors	46.35	7.36				

*Sig. at .05 level

Table 7 presents the mean ranking of five items, indicating perceptions regarding various aspects of project delivery in Nigeria. These items, ranked by their mean scores, include the existence of a relationship between cost, quality, and time in project delivery (3.647 > 2.50), the role of construction professionals, contractors, and project owners in improving project delivery in Nigeria (3.500 > 2.50), the importance of cost management in project delivery (3.471 > 2.50), the impact of maintaining quality on project delivery in Nigeria (3.412 > 2.50), and the significance of meeting project deadlines to project delivery in Nigeria (3.353 > 2.50). Furthermore, to assess the combined effect of time, quality, and cost on project delivery, Hypothesis 4 was tested, proposing a significant joint and relative effect of these variables on project delivery.

The analysis presented in Table 8 demonstrates a significant combined effect of time, quality, and cost on project delivery, indicating a positive correlation between project delivery and the independent variables (time, quality, and cost). The table reveals a coefficient of multiple correlations (R) of 0.884 and a multiple R square of 0.781, suggesting that when considered together, 77.6% (Adj. $R2 = 0.776$) of the variance in project delivery is explained by the independent variables. The joint contribution's significance was tested at $p < 0.05$ using the F-ratio, resulting in a significant outcome at the 0.05 level. Consequently, the null hypothesis was rejected, and the alternate hypothesis was accepted based on these findings.

Table 9 presents the significant relative contributions of independent variables to the dependent variable, expressed as beta weights, which reflect the effects of time, quality, and cost on project delivery. Using standardized regression coefficients, the study determines the relative contributions of these independent variables. Notably, quality factors ($\beta = 0.594$, $t = 15.310$, $p < 0.05$) emerge as the most influential contributor to the prediction, followed by time factors ($\beta = 0.563$, $t = 10.492$, $p < 0.05$), while cost factors ($\beta = 0.118$, $t = 2.198$, $p < 0.05$) exhibit a lesser relative contribution to project delivery. This suggests a relative effect of time, quality, and cost on project delivery. With a significance level of 0.05, the null hypothesis is rejected, and the alternate hypothesis is accepted based on these findings.

Table 7. Impact of time, quality and cost on project delivery in Nigeria.

S/N	Description	Weighted Sum	Mean Score	RII	Rank
1	Cost management is an important factor in project delivery	118	3.471	0.868	3rd
2	Cost overruns affect project delivery in Nigeria	108	3.176	0.794	6th
3	Maintaining quality has an impact on project delivery in Nigeria	116	3.412	0.853	4th
4	Meeting project deadlines is crucial to project delivery in Nigeria	114	3.353	0.838	5th
5	Project timelines affect project delivery in Nigeria	100	2.941	0.735	7th
6	Clients are realistic with respect to expectations of time, cost and quality at the outset of the project	85	2.500	0.625	9th
7	Clients are generally satisfied with clients with the time, cost and quality management of their projects	95	2.794	0.699	8th
8	Construction projects are completed within the client's agreed budget for the project	84	2.471	0.618	10th
9	There exist a relationship between cost, quality, and time in project delivery	124	3.647	0.912	1st
10	Construction professionals, contractors, and project owners play in improving project delivery in Nigeria	119	3.500	0.875	2nd

Table 8. Regression analysis project delivery and combined effect of time, quality and cost.

.R	R Square	Adjusted R Square	Std. Error of the Estimate		
0.884	0.781	0.776	2.64092		
Summary Regression Anova					
	Sum of Squares	Df	Mean Square	F	P	Remark
Regression	3625.061	3	1208.354	173.254	0.000	Sig.
Residual	1018.272	146	6.974			
Total	4643.333	149				

Table 9. Test of significance of the regression coefficients.

Variable	Unstandardize	d	Standardized Coefficients			
	Coefficients					
Model	(B)	Std. Error	Beta	t	Sig.	Remark
Constant	7.738	1.953	-	3.961	.000	-
Time	.335	.032	.563	10.492	.000	Sig.
Cost	.106	.048	.118	2.198	.029	Sig.
Quality	.450	.029	.594	15.310	.000	Sig

Discussion of Findings

The study examines factors influencing project delivery time and cost management in Lagos State's construction industry, Nigeria. It corroborates previous research by Oke and Ugoje (2013), showing a significant relationship between project duration and cost metrics such as initial and final costs, cost overrun, and project completion time. Increased costs of rectifying nonconforming work were linked to longer project completion times. Additionally, the study supports Ajayi and Oyeyipo's (2015) findings regarding relationships between project duration and initial contract sum, as well as initial and final contract periods. However, no such relationship was found with the final contract sum. Project duration accounted for a notable portion of initial and final project costs and contributed significantly to observe cost overruns. Despite highlighting effective quality management practices, echoing Okoye's (2022) emphasis on quality planning, challenges persist in Nigeria's construction industry, as outlined by Shinde et al. (2014). These include organizational commitment issues, lack of management support, inadequate attention to quality concerns, and deficient quality planning.

Conclusion

This study investigated the impact of time, cost, and quality control on project delivery within the construction industry in Lagos, Nigeria. The findings reveal significant deficiencies in time, cost, and quality control practices, with quality management plans rarely developed for construction projects and subsequent quality auditing lacking. As a result, quality management measures tend to be reactive rather than proactive, with little focus on continuous performance improvement. Thus, this study underscores the urgency of examining quality management practices in Nigeria's construction industry to identify barriers and enhance effectiveness. Hence, the need for construction sector stakeholders to put novel monitoring and evaluation (M&E) techniques into practice. In conclusion the traditional M&E must be replaced by the current approach of using M&E software for construction project management in Lagos, Nigeria.

References

Abdullahi, U., Bustani, S. A., Hassan, A., & Rotimi, F. E. (2019). Assessing quality management practice in Nigerian construction industry. *Journal of Construction Business and Management, 3*(2), 17-25.

Achi, O.F., Onukwube H. N., & Ajayi O.M. (2007). An assessment of quality management of building projects in Nigeria. *Proceedings: Construction and Building Research Conference. Royal Institute of Surveyors (COBRA)*. Georgia Tech. Atlanta USA, 6-7 September.

Adeniyi, T. A., Oyebanji, O. O., & Adeonipekun, P. A (2016). Floral diversity in the Wetlands of Ibeju-Lekki Area, Lagos, Nigeria. *Ife Journal of Science*, *18*(3). 729-737.

Ajayi, O., & Oyeyipo, O. (2015). Effect of rework on project performance in building project in Nigeria. *International Journal of Engineering Research & Technology (IJERT)*, *4*(02), February 2015.

Eskerod, P., Huemann, M., & Ringhofer, C. (2015). Stakeholder inclusiveness: Enriching project management with general stakeholder theory. *Project Management Journal*, *46*(6), 42-53.

Festus, A. O. (2021). Factors influencing claims management practices in the Nigerian Construction Industry. *FUTY Journal of the Environment*, *15*(2), 1-15.

Godwin, G. (2023). *Influence of labour management practices on project delivery of construction firms in Abuja* (Doctoral dissertation).

Hamid, A. R. A., Bah, A. U., Ba Hutair, A. A. M. A., Hatem, Z. M., Islam, M. S., Yunus, R., Zadran, B. G., Abba, N., Aminudin, E., & Zakaria, R. (2023). The challenges of maintenance work in the University of Sierra Leone. In *AIP Conference Proceedings*, *2712*(1). AIP Publishing.

Hussain, O. A., Moehler, R. C., Walsh, S. D., & Ahiaga-Dagbui, D. D. (2024). Minimizing cost overrun in rail projects through 5D-BIM: A conceptual governance framework. *Buildings, 14*(2), 478.

Mamman, E. J., & Umesi, E. R. (2022). Causes and effects of delay on public construction projects delivery in Nigeria.

Muhammad, A. M. (2021). *Evaluation of total quality management practices of contractors in building industry in Abuja, Nigeria* (Doctoral dissertation).

Ogbu, C. P., & Ehigiator-Irughe, R. (2020). Cost over-run in civil works: A case-study of engineering, procurement and construction (EPC) gas depot construction projects in Nigeria. *European Journal of Environment and Earth Sciences*, *1*(4).

Oke, A. E., & Ugoje, O. F. (2013). Assessment of duration cost of selected building projects in Nigeria. *International Journal of Quality & Reliability Management,* 30(7), 799-810.

Okoye, C. (2022). Risk management and quality projects delivery in Nigeria's construction industry. *IJCECEM*, *10*(2), 1-51.

Omopariola, E. D. (2021). Modelling the relationship between project payment systems, financial management strategies and construction organisation performance in South Africa.

Osegbo, C. U., Okolie, K. C., Okeke, A. U., Ezeokoli, F. O., & Akaogu, A. C. (2021). Quality management practices of building construction firms in project delivery in Anambra State, Nigeria. *International Journal of Progressive Research in Science and Engineering*, *2*(10), 113-121.

Pateman, J. (1986). Giving the building owner quality, *Building Technology and Management*, Chartered Institute of Building, October/November.

Robles, J. (2023). *Fast-track projects with cost and schedule overruns a supply chain management perspective* (Doctoral dissertation, Capella University).

Shinde, S. D., Gupta, A. K., & Desai, D. B. (2014). Impact of quality supervision on rework in Indian construction industry. *International Journal of Engineering Research and Technology*, *3*(10).

Uwakwe, I. S. (2017). The correlation between instructional leadership capacity of school principals and academic performance of students in secondary schools in South East Nigeria. *Journal of Education and Practice, 8*(33), 147-164.

A Scientometric Review of Resource Leveling Analysis Construction Projects

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Abstract

Activities defined in construction projects are aimed to be completed within a certain period. Management and planning of resources and activities are essential stages in achieving this goal. This study conducts a scientometric analysis on resource leveling topics in civil engineering. Sixty studies are collected from the WoS database. The bibliometric data is analyzed using Citespace software. The study is expected to be a resource guide for researchers working on resource leveling analysis.

Keywords: *construction project, project management, resource analysis*.

Introduction

One of the main objectives of the Resource leveling problem is minimizing fluctuations of resource usage in a project. Resource management is a critical issue in the construction sector, and it is used to reduce hiring and firing cycles during the construction process. Various techniques have been proposed for solving resource leveling problems in the last 20 years. Meta-heuristic methods are the most frequently used ones. This study provides a literature review based on a scientometric viewpoint with a resource-leveling application of a five-block construction project.

Literature Review

Construction resource optimization consists of several problems, such as Resource leveling, resource constraints, and resource allocation. However, various studies dealt with more than one kind of problem. Senouci and Eldin (2004) used a genetic algorithm to solve resource leveling and resource-constrained project scheduling. Heuristic methods are one of the initial methodologies to solve resource leveling problems Burgess and Killebrew (1962). Initial approaches are based on integer and linear programming techniques. One of the initial studies was by Karaa and Nasr (1986), in which mixed linear integer programming was used. Easa (1989) used integer programming techniques to optimize resource leveling in construction projects. Harris (1990) applied heuristic methods to solve resource-leveling problems by minimizing the moment value of resource-usage histograms. Resource leveling problem is still attracting researchers because of variating different construction project types, stochastic and variating resource usage (Li et al., 2015), and applying activity splitting on schedule (Alsayegh & Hariga, 2012).

Genetic algorithms are one of the meta-heuristic optimization methods frequently used for solving resource-leveling problems. One initial approach is genetic algorithms (Leu et al., 2000). Hybrid methods also apply to resource leveling problems (Kyriklidis et al., 2014). Big Bang—Big Crunch Optimization is another method for solving resource leveling and resource-constrained project scheduling (Toklu, 2018).

In construction projects, different situations, such as weather conditions and financial issues, may affect construction durations and cost values. Methodologies that involve stochastic processes can model the variability of construction processes. Zahraie and Tavakolan (2009) developed a multiobjective model that minimizes project duration, cost, and resource moments. Gwak and Lee (2021) applied resource leveling methodology in stochastic environments. Li et al. (2015) used the tabu search technique to solve stochastic resource leveling problems.

Resource leveling problems are imported to Linear and line of balance (LOB) type schedules. These kinds of schedules include repetitive tasks (such as in highway, pipeline, and tunnel projects) to be modeled inside LOB schedules. The initial known approach of solving line of balance techniques of linear projects is using linear programming techniques (Mattila & Abraham, 1998). Tang et al. (2014) solved resource leveling issues in line-of-balance projects using constraint programming.

Scientometric Analysis

Scientometric analyses have been used frequently in literature reviews in the last decade. Citespace is one software package object to develop bibliometric graphs and relationships on research articles (Chen, 2006). Before using scientometric techniques, a text file from the WoS (Web of Science) database that includes all information with reference lists is downloaded. In the WoS database, the query “TS=("resource leveling”) AND (SU= "Construction & Building Technology" or WC="Construction & Building Technology")” is searched, and 60 articles were given as a result. A text file containing all information citing studies belonging to these 60 papers is downloaded. There are 2652 articles, and 468 proceeding papers appear as given in references. Citespace software analyses this data file and constructs a network diagram using the bibliometric information in the downloaded text file (e.g., title, abstract, cited references).
Figure 1 shows the network of referenced studies. Citespace selects the higher cited articles before developing the graph, g-index is the default option for the selection, and k parameter is chosen as 25. After the selection, 364 nodes and 883 links remain in
Figure 1.

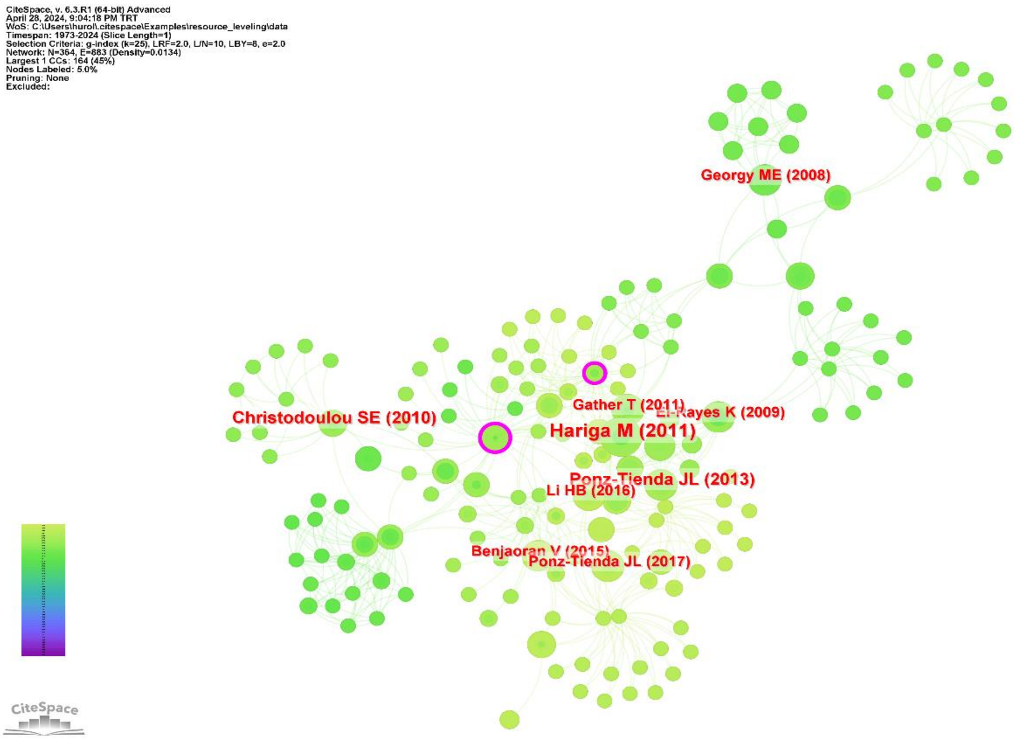

Figure 1: Network of references.

The fonts of the top cited studies in
Figure 1 depend on the citation number. Each node represents a reference for one of the 60 studies. Each connection between nodes represents a citation relationship between two studies. Studies can be clustered using these citation relationships, as seen in
Figure 2. Three labeling tools (Title, keyword, WoS subject category) can tag the clusters with the most representative terms. It can be chosen to extract such terms from the titles of papers citing the cluster, their abstracts, or keyword lists.

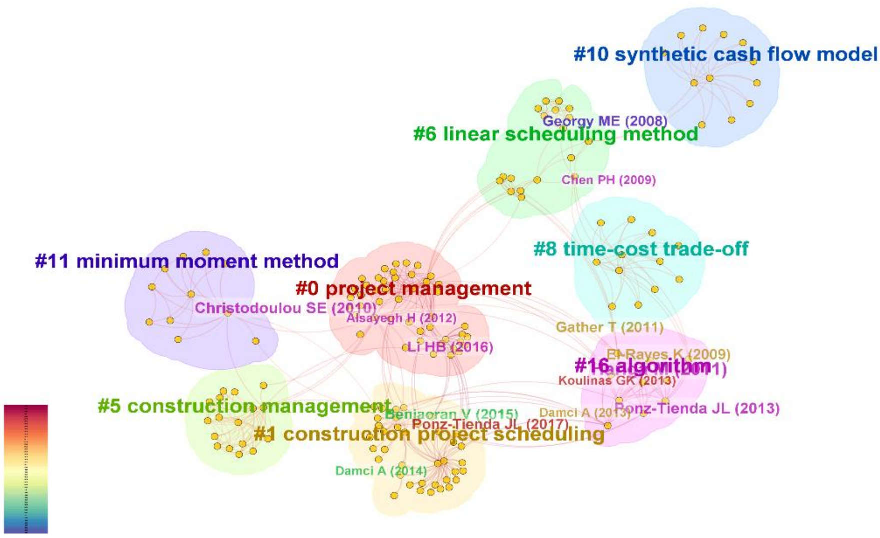

Figure 2: Clusters named with keywords.

8 clusters appeared to be named with keywords. Table 1 gives the top cited studies on the field with their cluster IDs. Some articles' clusters are not labeled because of the inadequate number of members they include. Citespace obtains the citation statistics for each reference and writes it under the "Freq" column. The "Cluster Keyword" column lists the cluster's label, which includes the most representative keyword in the related cluster. The "Keywords from resources" column includes keywords taken directly from the WoS database. There is consistency between the last two columns.

Table 1. Top-cited articles with cluster ids.

Freq	Label	Cluster ID	Cluster Keyword	Keywords From Resources
9	(Hariga & El-Sayegh, 2011)	16	Algorithm	Analytical techniques, Leveling, Optimization models, Splitting
9	(Senouci & Eldin, 2004)	7	Not Available	Construction management; Algorithms; Scheduling; Mathematical programming
6	(Christodoulou et al., 2010)	11	Minimum Moment Method	Resource-constrained scheduling, Leveling, Minimum moment method, Entropy
6	(Ponz-Tienda et al., 2013)	16	algorithm	Project scheduling, Resource leveling, Genetic algorithms, Benchmarking
5	(Chan et al., 1996)	2	Not Available	Heuristics, Projects
5	(Gather et al., 2011)	16	algorithm	Resource levelling, Renewable resources, Project scheduling, Enumeration, Branch-and-bound
5	(El-Rayes & Jun, 2009)	16	algorithm	Genetic Algorithms, Model, Optimization
5	(Benjaoran et al., 2015)	1	construction project scheduling	Construction scheduling, precedence relationship, sresource utilization, resource levelling, genetic algorithm
5	(Georgy, 2008)	6	linear scheduling method	linear project, linear scheduling method, resource scheduling, resource leveling, genetic algorithms, CAD, AutoLISP programming
5	(Li & Demeulemeester, 2016)	0	project management	Project scheduling, Robust resource leveling, Stochastic activity durations, Genetic algorithm

Figure 3 shows the timeline plotting for each represented cluster. The "project management" cluster shows a consistent trendline during the period. The second consistent cluster is "construction project scheduling." The articles about "project management" and "consistent project scheduling" have a chance to be cited in recent years. The other clusters have no identical citation statistics in about five years. Another interesting point in Figure 3 is that articles that belong to the "algorithm" cluster got higher citation statistics between 2009 and 2015. However, after 2015, the citation number has diminished.

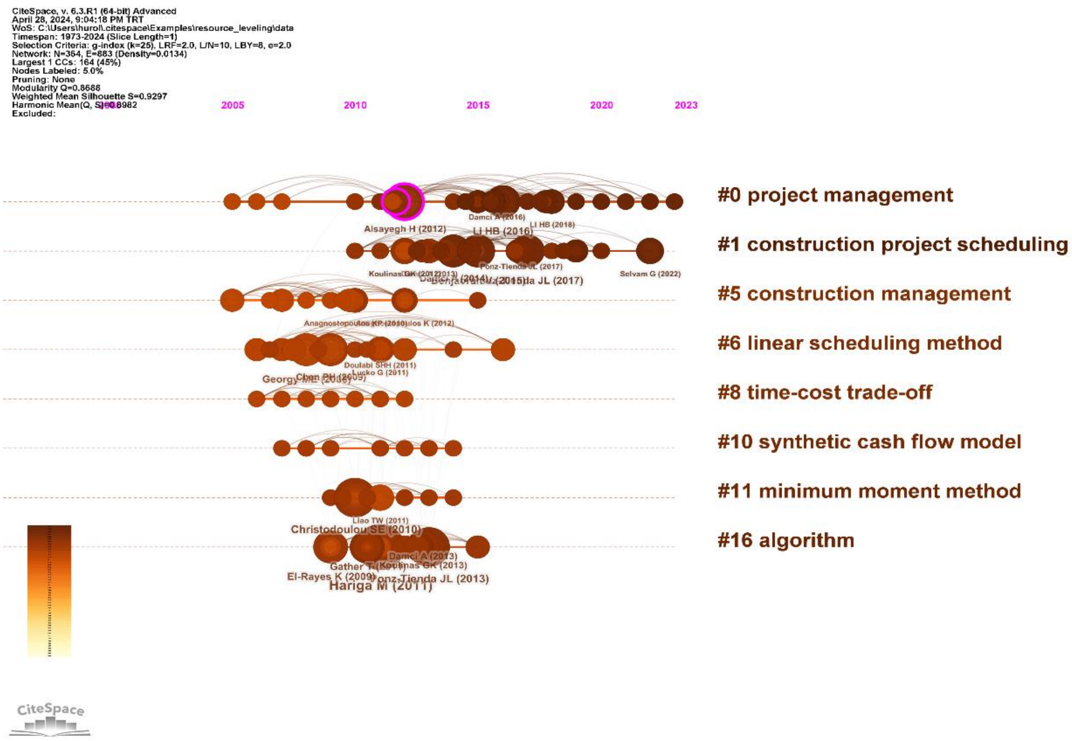

Figure 3: Timeline view of each cluster.

Conclusion

Resource leveling analysis is an essential issue in the management of construction projects. When we look at successful projects, we see that resources are used optimally. The main factors of project success are time and cost management, which depend on good resource leveling analysis management.

Planning is also done with resource-leveling analysis before the implementation phase of the projects. The relevant experts meticulously carry out this process. Studies are being carried out by relevant researchers worldwide to make this process more successful. In this study, studies on resource leveling analysis are discussed and examined. This study is undertaken as a scientometric examination of resource leveling analysis of construction projects. Within the scope of this study, studies on resource leveling analysis are examined for 60 obtained studies from the WoS database. More than 3000 studies have been cited and analyzed using Citespace software. It is expected to be a resource guide for researchers working on resource leveling analysis. The primary result of this study is topics that drive forward "project management" "and "construction project scheduling," as the first keywords tend to be cited continuously.

References

Alsayegh, H., & Hariga, M. (2012). Hybrid meta-heuristic methods for the multi-resource leveling problem with activity splitting. *Automation in Construction*, *27*, 89–98. https://doi.org/10.1016/j.autcon.2012.04.017

Benjaoran, V., Tabyang, W., & Sooksil, N. (2015). Precedence relationship options for the resource levelling problem using a genetic algorithm. *Construction Management and Economics*, *33*(9). https://doi.org/10.1080/01446193.2015.1100317

Burgess, A. R., & Killebrew, J. B. (1962). Variation in activity level on a cyclical arrow diagram. *Journal of Industrial Engineering*, *13*(2), 76–83.

Chan, W.-T., Chua, D. K. H., & Kannan, G. (1996). Construction resource scheduling with genetic algorithms. *Journal of Construction Engineering and Management*, *122*(2), 125–132. https://doi.org/10.1061/(ASCE)0733-9364(1996)122:2(125)

Chen, C. (2006). CiteSpace II: Detecting and visualizing emerging trends and transient patterns in scientific literature. *Journal of the American Society for Information Science and Technology*, *57*(3), 359–377. https://doi.org/10.1002/asi.20317

Christodoulou, S. E., Ellinas, G., & Michaelidou-Kamenou, A. (2010). Minimum moment method for resource leveling using entropy maximization. *Journal of Construction Engineering and Management*, *136*(5). https://doi.org/10.1061/(asce)co.1943-7862.0000149

Easa, S. M. (1989). Resource leveling in construction by optimization. *Journal of Construction Engineering and Management*, *115*(2). https://doi.org/10.1061/(asce)0733-9364(1989)115:2(302)

El-Rayes, K., & Jun, D. H. (2009). Optimizing resource leveling in construction projects. *Journal of Construction Engineering and Management*, *135*(11). https://doi.org/10.1061/(asce)co.1943-7862.0000097

Gather, T., Zimmermann, J., & Bartels, J. H. (2011). Exact methods for the resource levelling problem. *Journal of Scheduling*, *14*(6). https://doi.org/10.1007/s10951-010-0207-8

Georgy, M. E. (2008). Evolutionary resource scheduler for linear projects. *Automation in Construction*, *17*(5). https://doi.org/10.1016/j.autcon.2007.10.005

Gwak, H. S., & Lee, D. E. (2021). Stochastic resource leveling optimization method for trading off float consumption and project completion probability. *Computer-Aided Civil and Infrastructure Engineering*, *36*(8). https://doi.org/10.1111/mice.12668

Hariga, M., & El-Sayegh, S. M. (2011). Cost optimization model for the multiresource leveling problem with allowed activity splitting. *Journal of Construction Engineering and Management*, *137*(1). https://doi.org/10.1061/(asce)co.1943-7862.0000251

Harris, R. B. (1990). Packing method for resource leveling (Pack). *Journal of Construction Engineering and Management*, *116*(2). https://doi.org/10.1061/(asce)0733-9364(1990)116:2(331)

Karaa, F. A., & Nasr, A. Y. (1986). Resource management in construction. *Journal of Construction Engineering and Management*, *112*(3). https://doi.org/10.1061/(asce)0733-9364(1986)112:3(346)

Li, H., & Demeulemeester, E. (2016). A genetic algorithm for the robust resource leveling problem. *Journal of Scheduling*, *19*(1). https://doi.org/10.1007/s10951-015-0457-6

Li, H., Xu, Z., & Demeulemeester, E. (2015). Scheduling policies for the stochastic resource leveling problem. *Journal of Construction Engineering and Management*, *141*(2). https://doi.org/10.1061/(ASCE)CO.1943-7862.0000936

Mattila, K. G., & Abraham, D. M. (1998). Resource leveling of linear schedules using integer linear programming. *Journal of Construction Engineering and Management*, *124*(3). https://doi.org/10.1061/(asce)0733-9364(1998)124:3(232)

Ponz-Tienda, J. L., Yepes, V., Pellicer, E., & Moreno-Flores, J. (2013). The resource leveling problem with multiple resources using an adaptive genetic algorithm. *Automation in Construction*, *29*, 161–172. https://doi.org/10.1016/j.autcon.2012.10.003

Senouci, A. B., & Eldin, N. N. (2004). Use of genetic algorithms in resource scheduling of construction projects. *Journal of Construction Engineering and Management*, *130*(6), 869–877. https://doi.org/10.1061/(ASCE)0733-9364(2004)130:6(869)

Tang, Y., Liu, R., & Sun, Q. (2014). Schedule control model for linear projects based on linear scheduling method and constraint programming. *Automation in Construction*, *37*, 22–37. https://doi.org/10.1016/j.autcon.2013.09.008

Toklu, Y. C. (2018). Application of big bang - big crunch optimization to resource constrained scheduling problems. *KSCE Journal of Civil Engineering*, *22*(12). https://doi.org/10.1007/s12205-017-1549-y

Zahraie, B., & Tavakolan, M. (2009). Stochastic time-cost-resource utilization optimization using nondominated sorting genetic algorithm and discrete fuzzy sets. *Journal of Construction Engineering and Management*, *135*(11). https://doi.org/10.1061/(asce)co.1943-7862.0000092

Application of Maturity Method with Temperature Sensors to Estimate Compressive Strength of Sustainable Concrete for Real-Time Formwork Planning

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Abstract

The concept of maturity in concrete is a function of concrete temperature and time during which concrete gains strength. The maturity of the concrete is of great importance in terms of formwork process time and concrete strength during building construction. In this study, the relationship between maturity values and compressive strengths of sustainable concrete produced with various waste and recycled materials that can be used instead of cement (Fly Ash, Silica Fume, Natural Pozzolan) was examined. In the study, Arduino development kit and DS18B20 temperature sensor were used and maturity index values were calculated. The correlation between 1, 3, 7, 14, 28-day compressive strength and maturity values was investigated with Nurse – Saul equations. A and B coefficients in the Nurse - Saul equation were calculated for concrete with different recycled admixtures. With this method, real-time planning can be made during construction, especially when the air temperature is low, and sufficient strength for the removal of the formwork can be monitored.

Keywords: *concrete, formwork, maturity, planning, sensor.*

Introduction

Concrete is a building material created by combining cement, aggregate (sand, gravel, stone), water and, when necessary, additives in certain proportions. As a result of the reactions of these materials, the concrete, which has a plastic consistency, begins to harden (set) and gain strength over time. The compressive strength of concrete is of great importance to ensure the durability and safety of structures. Concrete used as a building material must have the compressive strength determined in the structural systems (foundations, columns, beams) and building elements (slabs, walls). This strength affects the carrying capacity and durability of structures. In this context, determining the compressive strength of in-situ concrete is important. Various methods have been developed for this. These methods are divided into two groups: destructive and non-destructive. Destructive strength tests aim to measure the strength properties of concrete samples by applying certain forces. These tests include compressive strength testing, tensile strength testing and bending strength testing. While compressive strength testing measures the strength by the compressive force applied to concrete samples, tensile strength testing and flexural strength testing evaluate the tensile and flexural strength of concrete. Non-destructive strength tests aim to measure the strength of concrete without the need to destroy the samples (Carufel et al., 2018). Based on the concrete maturity-strength relationship, a method that can be included among the non-destructive methods has been developed. The maturity of concrete is a time-dependent function of the temperature that occurs as a result of the hydration reactions that begin after the concrete is poured. With this function, predictions can be made about the early age (days 1, 3, 7, 14, 28) strengths of concrete, which are important for planners. Thanks to this method, labor times and job follow-up times can be shortened. As a general rule, the formwork in the constructed structures is dismantled within 3 to 7 days. However, due to environmental factors (ambient temperature, curing time, chemical factors, etc.), dismantling the formwork before the concrete reaches the predicted strength may cause accidents. As an example, there is an accident that occurred in 1973 during the construction of the Skyline Plaza Tower. Professor Ingvar Schousboe, who was appointed as an expert by the Fairfax district, stated that the cause of this accident was due to the removal of the molds and the pouring of the upper layer of concrete before the concrete reached sufficient maturity (Carufel et al., 2018).

Concept of Maturity in Concrete

The maturity of concrete is defined as the cumulative sum of temperature values occurring in the concrete during the period when the concrete gains strength. The term maturity is a method for defining the heat-time relationship, one of the factors that play a role in the strength gain of concrete. The maturity method enables a reliable prediction to be made about the future strength of the placed concrete by monitoring its early age strength development. The basis of this method is based on the steam cure application applied in England in the late 1940s and early 1950s (Dilly & Ledbetter, 1984; Ha et al., 2021). Time and temperature are among the main factors affecting the strength of concrete. Other factors such as water-cement ratio, cement type and amount, mold properties, ambient humidity and temperature should also be taken into consideration. In cases where secondary factors are constant or ignored, "Degree of Maturity" is calculated using time and temperature variables to evaluate strength development (Dilly & Ledbetter, 1984; Maraşlı, 2019). The two most common methods have been developed to calculate concrete maturity degree. These methods are “Saul-Nurse (Temperature-Time Factor) and Arrhenius (Equivalent Age) mathematical functions. In the early 1950s, Saul defined concrete maturity as a product of setting temperature and time. In this way, it was possible to make a reliable estimate about the in-situ strength of concrete. This method was developed specifically for accelerated cure methods. The relationship Saul developed to calculate concrete maturity can be seen in Equation 1.

$$M = \sum (T - T_0) \times \Delta_t \tag{1}$$

M: Maturity index (C^o *days or C^o *hours)
T: Average temperature that the concrete is exposed to (C^o)
T_0: Base temperature C^o (usually 0 C^o and 10 C^o are accepted.)
Δt: Represents the cure time interval (day or hour).

The maturity index M calculated from this equation is called the temperature-time factor in today's terminology. The temperature change (t*) and temperature-time factor that the concrete is exposed to are usually shown in Figure 1. In this graph, the temperature-time factor of concrete at any age is the area between the temperature curve and the underlying temperature

(T_0). The baseline temperature is a temperature at which concrete is assumed to stop gaining strength.

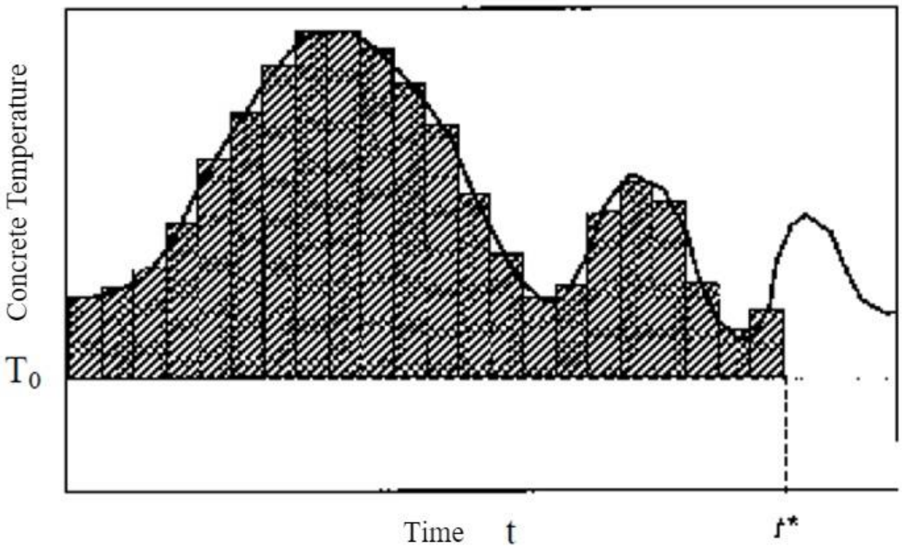

Figure 1: Temperature change to which concrete is exposed and temperature-time factor calculated according to equation 1

(Hansen & Pedersen, 1977) proposed a new method using the recorded temperature change to calculate the maturity index of concrete. This method describes the effect of chemical reactions on temperature based on the Arrhenius equation. The maturity index calculation method is based on determining the "equivalent age" of concrete.

This new function predicts the maturation process of concrete based on temperature change. Equivalent age (Equation 2) represents the level of maturity that concrete will reach at a given temperature profile. Using the Arrhenius equation, the maturation process of concrete is modeled by combining temperature and time factors.

$$t_e = \sum e^{-Q(\frac{1}{T_a}-\frac{1}{T_s})\Delta t} \quad (2)$$

t_e: Equivalent age (days or hours) at the time of specific temperature
Q: Activation energy divided by gas constant (Q=E/R) R=general gas constant, 8.314 J/mol-K
T_a: Average temperature value (K) to which the concrete is exposed in the Δt range
T_s: Reference Temperature (K).

Maturity – Strength Relation

Many researchers have tried to explain the relationship between concrete maturity and strength with different approaches at different times. Among these, the relation that is most widely used and used in the literature was created by (Plowman, 1956).This relation (Equation 3) is the formula that shows the relationship between concrete strength and maturity. With this approach, it can be predicted at what maturity level the concrete will reach which strength. The compressive strength – maturity relationship is shown in Figure 2.

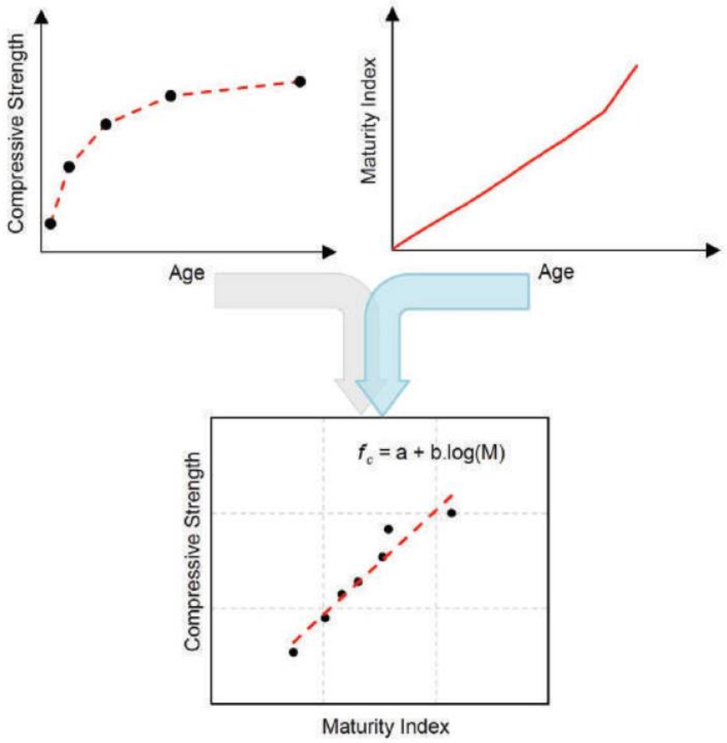

Figure 2: Concrete compressive strength-maturity relationship (Carufel et al., 2018).

$$S = a + b \times \log(M) \tag{3}$$

S: Compressive Strength of Concrete (MPa)
M: Maturity Index (degree) (C° *hours or C° *days)
a and b: regression coefficients are stated by Plowman (Plowman, 1956). Figure 3 shows the a and b coefficients obtained in Plowman's study (varies depending on cement type and water content) (Choi et al., 2020).

	Constants		4 in. cube strength at 35,600°F hr (lb/in²)
	A	*B*	
Plowman	12·5	51·5	3,600
	25	51	4,600
	24	49·4	5,200
Road Note No. 4	8·3	58·3	1,800
	9·1	59	2,200
	10·7	57·1	2,800
	12·1	56·9	3,300
	22·1	49·5	4,750
	30·5	45·8	5,900
	39·2	39·2	7,400
	50·6	31·9	9,100

Strength (lb/in²) after				Constants		Zone
35,600°F hr	17,800°F hr	8,900°F hr	3,800°F hr	*A*	*B*	
0– 2,500	0–2,050	0–1,620	0–1,090	3·1	62·4	I
2,500– 5,000	2,050–4,250	1,620–3,520	1,090–2,620	17·3	53	II
5,000– 7,500	4,250–6,660	3,520–5,700	2,620–4,630	31·8	43·6	III
7,500–10,000	6,660–9,080	5,700–8,180	4,630–7,080	46·2	34·3	IV

Figure 3: Constants a, b and their ranges for the Plowman function (Plowman, 1956).

Materials and Methods

In this study, CEM I 42.5R cement purchased from Konya Cement Factories was used. 4 different mixtures were prepared by replacing silica fume, fly ash and natural posing cement with 15% cement by weight. The w/b ratio of the mixtures was taken as 0.5. Concrete mixtures were prepared with the concrete mixer and placed in molds measuring 15x15x15 cm. Three samples for each mixture and one sample to place the temperature sensor were prepared for compressive strength measurements on days 1, 3, 7, 14 and 28. After the samples were kept in the laboratory environment for 24 hours, they were removed from the molds and cured in a curing pool at 22 ℃. The compressive strength of the samples prepared on the specified days was calculated by taking the average of all three samples. Arduino UNO development board and DS18B20 temperature sensor were used for maturity index measurements. By using the interface of the Arduino kit and the libraries available in this interface, temperature measurements of 4 samples can be made simultaneously. The DS18B20 temperature sensor used in the study is a waterproof sensor with digital output and an accuracy of ±0.5 ℃. The image of the sensor is shown in Figure 4.

Figure 4: DS18B20 sensor.

A total of 4 data inputs on the DS18B20 temperature sensor board were connected to each other and transferred to the Arduino data input pin. Data could be imported as an Excel file with the Arduspreadsheet plug-in. Thanks to the written code, the sensors took measurements at 30-minute intervals and saved them to Excel. The data collected for 28 days were processed according to the Nurse-Saul maturity equation and maturity values were calculated. The image of the experimental setup is presented in Figure 5.

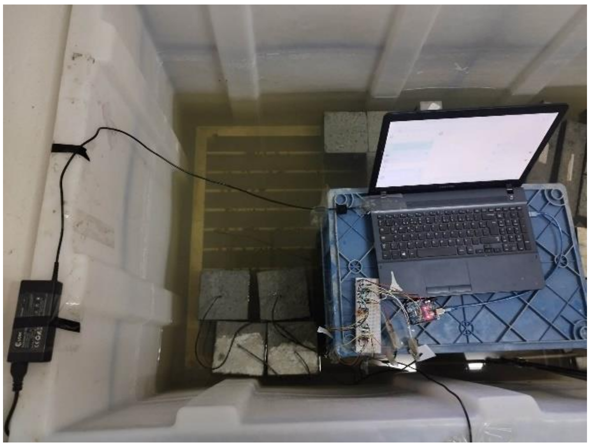

Figure 5: The experimental setup.

Temperature data taken from the concrete was used to calculate the maturity index with the Nurse – Saul equation. A and b coefficients were obtained by obtaining the logarithmic trend curve and function between the maturity index value obtained and the compressive strengths obtained on days 1, 3, 7, 14 and 28.

Experimental Results

The compressive strength results applied to the prepared samples on days 1, 3, 7, 14 and 28 are presented in Figure 6. In the strength results, the strength values of the reference sample were observed to be the highest on days 1 and 3. On the 7th and 14th days, increases were observed in the compressive strength of the samples containing silica fume compared to the reference sample. At the 28th day strength, the compressive strengths of samples containing silica fume and fly ash are 16.4% and 5.2% higher, respectively, than the reference. The compressive strength of natural pozzolan added concrete was measured to be 6.8% lower than the reference sample.

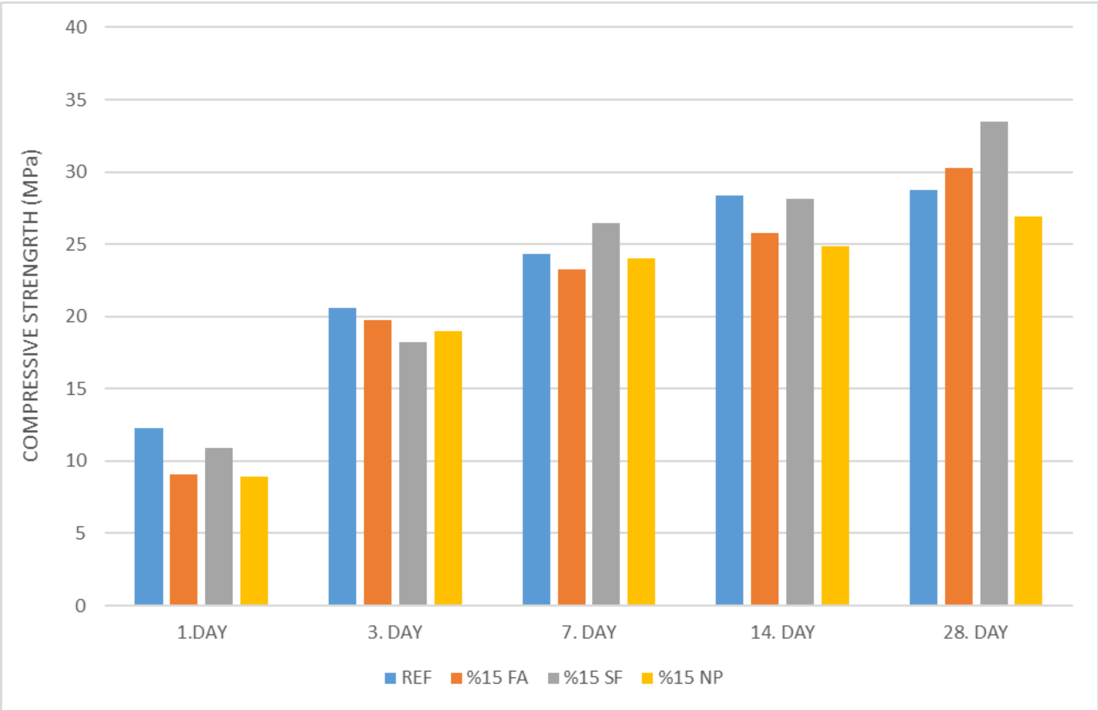

Figure 6: Compressive strengths of concrete samples.

The temperature-time graphs of the samples are presented in Figure 7. The graphs show that increases in temperature were observed in the first 24 hours as a result of hydration reactions.

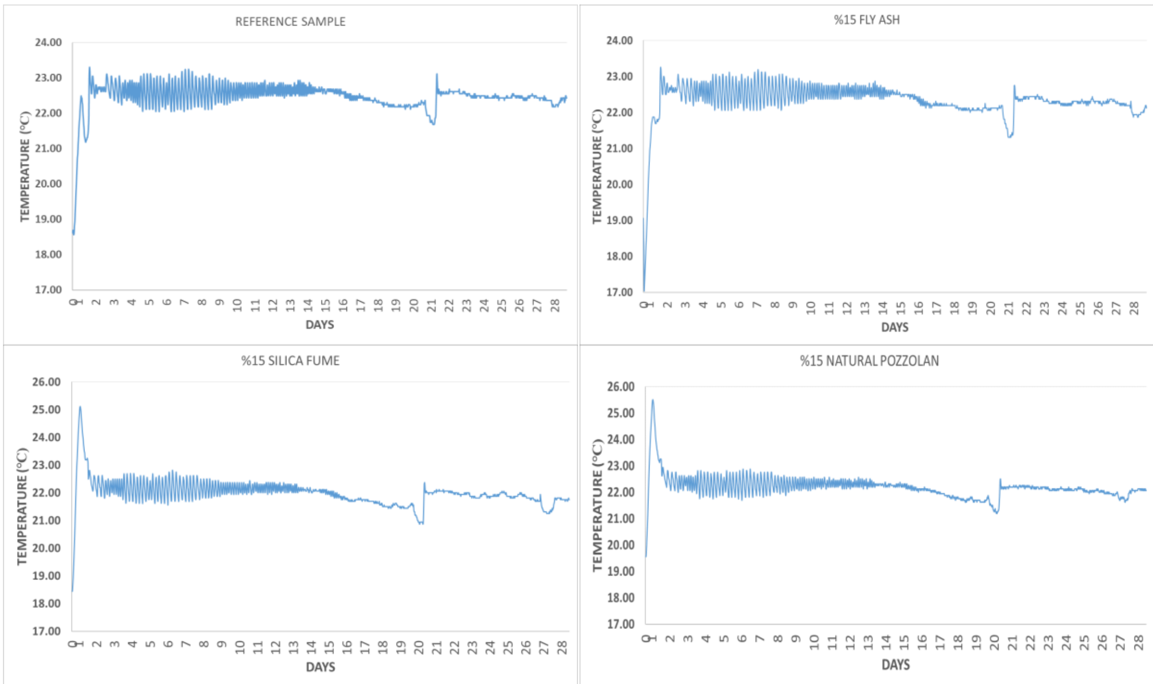

Figure 7: Temperature time graphs of samples.

The T_0 temperature value specified in the Nurse-Saul equation is taken as 0 °C as stated in ASTM C1074 (ASTM C1074, 2021). The relationship between maturity values and compressive strengths measured on days 1, 3, 7, 14 and 28 is shown in Figure 8, Figure 9, Figure 10 and Figure 11.

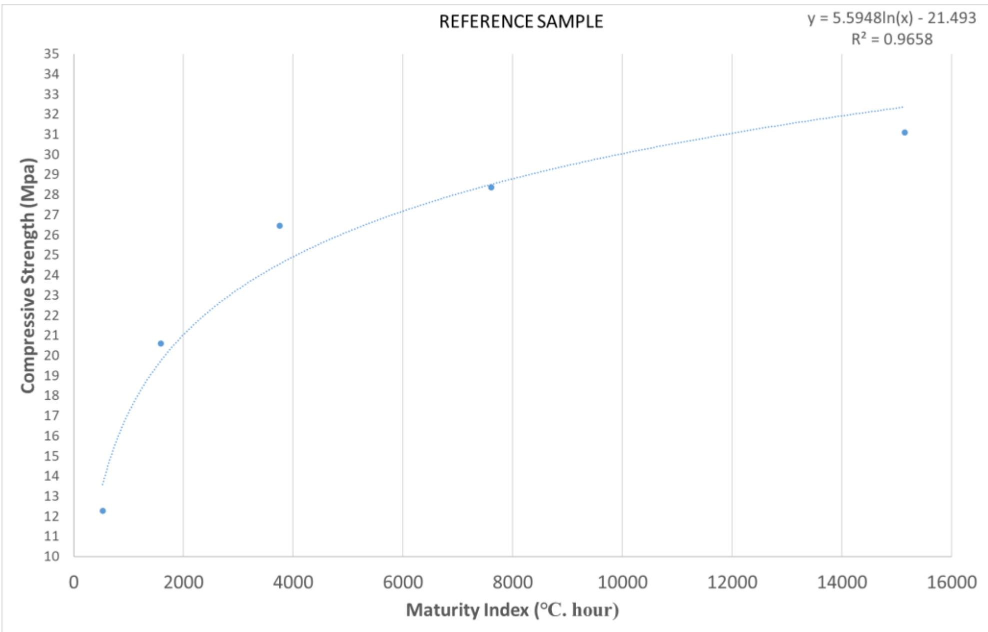

Figure 8: Maturity index-strength graph of reference concrete.

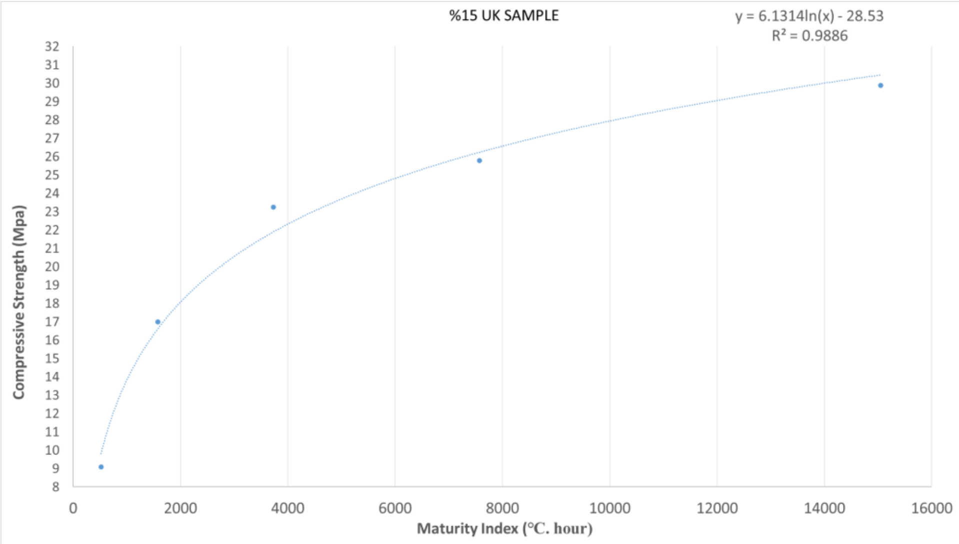

Figure 9: Maturity index-strength graph of concrete containing 15% UK.

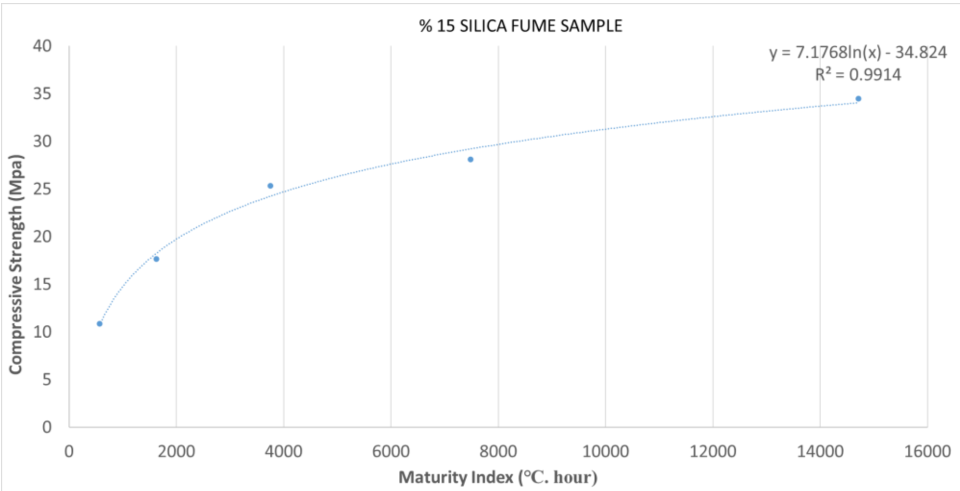

Figure 10: Maturity index-strength graph of concrete containing 15% SF.

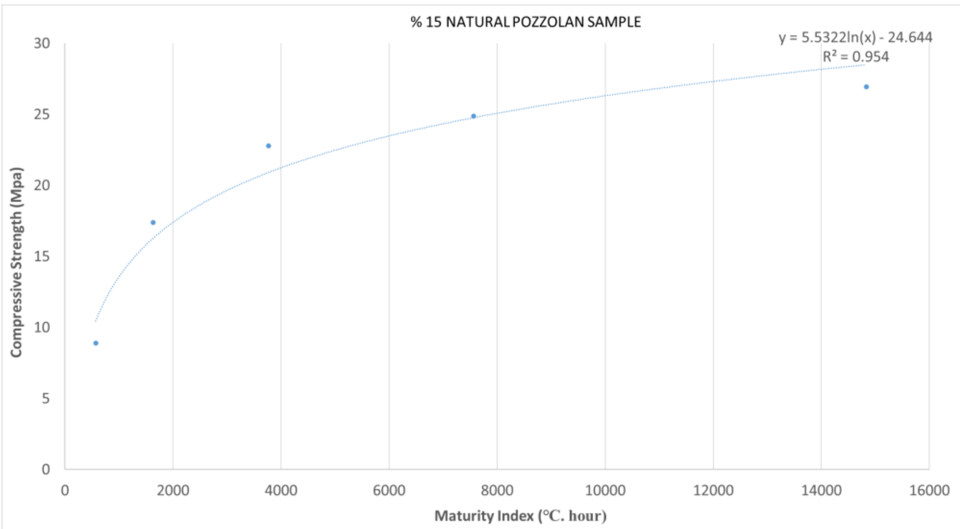

Figure 11: Maturity index-strength graph of concrete containing 15% NP.

Table 1 shows the functions and R^2 values obtained as a result of the maturity-strength relationship. As R^2 values (coefficient of determination) approach 1, the relationship between experimental data is stronger. In this study, it was observed that the relationship between strength and maturity was strong.

Table 1. Functions obtained for different samples.

SAMPLE	NURSE – SAUL FUNCTION	R^2	A	B
REFERENCE	y = 5.5948ln(M) - 21.493	$R^2 = 0.9658$	- 21.493	5.5948
%15 UK	y = 6.1314ln(M) - 28.53	$R^2 = 0.9886$	- 28.53	6.1314
%15 SD	y = 7.1768ln(M) - 34.824	$R^2 = 0.9914$	- 34.824	7.1768
% 15 DP	y = 5.5322ln(M) - 24.644	$R^2 = 0.954$	- 24.644	5.5322

Discussion and Conclusion

As a result of the research, the results presented below were reached.

• The mechanism established with Arduino and DS18B20 temperature sensor can be used to measure, record and store the maturity of concrete during curing, such as maturity measuring devices also known as maturity meters.
• Maturity – strength relationship was examined by the Nurse – Saul method and the % error was calculated as < 4.6%. This indicates that the Nurse-Saul method can be used in concretes with different pozzolan additives.
• It has been observed that concretes with Pozzolan additives reach higher temperatures than the reference sample within the first 24 hours. This shows that pozzolan additives accelerate hydration reactions and cause an increase in temperature.
• It has been observed that in early age strengths, pozzolan additives cause a decrease in compressive strength compared to the reference sample.
• The purpose of this system is to determine the sufficient strength for the formwork process by the maturity method in order to make real-time planning at the construction site.
• After pouring the concrete, maturity values can be calculated thanks to temperature sensors, and strength estimation can be made by using the obtained coefficients and maturity measurements in the Nurse-Saul equation.
• With this method, the process of taking concrete samples during concrete pouring by building inspection companies can be eliminated.
• In examining the maturity strength relationship in ASTM standards, compressive strengths are measured on days 1, 3, 7, 14 and 28.
• When the temperature data is examined, it is seen that the fluctuation in temperature decreases starting from the 10th day and a more linear temperature data is obtained.
• The early age of concrete is very important in estimating strength using the maturity method.
• Making strength measurements more frequently in the first 10 days may enable a more sensitive examination of the maturity-strength relationship.

References

ASTM C1074. (2021). *Standard practice for estimating concrete strength by the maturity method*. ASTM.

Carufel, S. De, Fahim, A., Ghods, P., & Alizadeh, A. (2018). *Concrete maturity from theory to* *application* (1st ed.). Giatec Scinetific Inc.

Choi, Y.-H., Han, M.-C., & Lee, Y.-J. (2020). Strength correction factors due to temperature drop of structural concrete under low temperature by the equivalent age method. *Journal of the Korea Institute of Building Construction*, *20*(5), 409–416.

Dilly, R. L., & Ledbetter, W. B. (1984). Concrete strength based on maturity and pullout. *Journal of Structural Engineering*, *110*(2), 354–369. https://doi.org/10.1061/(asce)0733-9445(1984)110:2(354)

Ha, N., Kim, H.-S., Lee, H.-S., & Lee, S. (2021). Monitoring concrete compressive strength using IoT-based wireless sensor network. *2021 IEEE International Conference on Consumer Electronics-Asia (ICCE-Asia)*, 1–3. https://doi.org/10.1109/ICCE-Asia53811.2021.9641999

Hansen, P. F., & Pedersen, E. J. (1977). *Maturity computer for controlled curing and hardening of concrete*. https://api.semanticscholar.org/CorpusID:134255342

Maraşlı, M. (2019). *Development of a prediction model of bending and compressive strengths in glass fiber reinforced concrete with the maturity index method*. Duzce University, Institue of Science, Master Thesis.

Plowman, J. M. (1956). Discussion: Maturity and the strength of concrete. *Magazine of Concrete Research*, *8*(24), 169–183. https://doi.org/10.1680/macr.1956.8.24.169

An Investigation into the Progress Monitoring Studies in Construction Management

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Abstract

This study aims to investigate the state-of-the art of the literature on the progress monitoring studies in construction industry and to present a categorization and mapping in the relevant field. Within the scope of paper, construction progress monitoring (CPM) researches have been scanned with the determined filters from the main databases (i.e., ScienceDirect, ASCE, Taylor&Francis Online). Publications have been analyzed and classified under three main categories as "review", "supportive" and "model suggesting" studies. The studies under review category mainly investigate, analyze and evaluate the CPM literature from various perspectives, whereas supportive studies -despite not directly suggesting a specific model- focused on increasing the performance of potential-future models to be generated for progress monitoring in construction. Literature review findings also revealed that the remaining studies may be categorized under "model suggesting" title by proposing a conceptual or practical methodology to assess the actual situation of implementation in construction field. The high number of studies included in the last category opened the door for further researches. It was determined that the studies in this field differ from each other especially in terms of data collection and processing methods, specific construction areas they focus on and input sources, so the studies were evaluated accordingly. This study can contribute to progress monitoring researches in the field of civil engineering, architecture and interior architecture especially for construction and finishing works.

Keywords: *data gathering, data processing, digitalization, literature review, progress monitoring.*

Introduction

It is hard to address Construction Industry (CI) as an efficient industry with its 1% annual productivity increase in the last 20 years after 2000 that corresponds nearly one third of global economy value (Ribeirinho et al., 2020). Inefficiency of CI is not a fresh topic in literature as Nahangi and Haas (2014) noted that delayed awareness of incorrect application at site causes nearly 10% increase in construction costs. Most AEC companies spend human and other sources for only gaining progress monitoring data from construction sites (Chen et al., 2020).

AEC sector is experiencing an increasing need for an enhanced and more productive method of monitoring construction progress to supplant the cumbersome, error-prone, and labor-intensive manual method (Zhang et al., 2022). Considering the potential of CI's ability to provide real time and verified data, most decision makers in sector are oriented towards digitization to evaluate actual situation more precisely and interpret the trends to manage future decisions actively (Meisels, 2020). Getting progress monitoring easier, more precise and consistent, achieving more efficient project management is needed to make more accurate earned value analyzes, resource leveling, rational schedule and cost plan revisions possible (Kopsida & Brilakis, 2020).

Methodology

Significance of project management in CI is emphasized by the sources previously referred. In order to contribute the literature with a new approach for digital progress monitoring, a comprehensive review of the literature on technology driven innovations & enhancements in monitoring area in a synchronic way is main focus of this paper.

This research aimed to identify state-of-the-art of the literature by focusing on technologies employed for construction progress monitoring (CPM). The research objectives were to examine employed CPM technologies; to investigate technologies for construction project management particularly focusing on CPM, and to identify and compare models, methods and focused areas of publications in the literature. The study reached a categorization that focuses on papers to clarify specific potential fields for increasing efficiency in progress monitoring in construction.

During the research carried out prior to the systematic literature review, it was observed that data acquisition and processing in the field of CPM are two of the most important concepts of research. In this context, the research was continued by searching the databases with some synonym versions of the most preferred keywords, which are thought to give the most relevant results. As a result of this research, it was seen that the approaches of some studies to the subject differed from others and could be grouped within themselves. Subsequently, it was decided to search the databases in order to group these studies systematically and to evaluate all articles on the identified topics.

Table 1. Research frame of the study.

<table>
<tr><td rowspan="4">data access</td><td>time period</td><td colspan="3">2017 / 2024</td></tr>
<tr><td>database</td><td>ScienceDirect</td><td>ASCE</td><td>Taylor&Francis</td></tr>
<tr><td>keywords</td><td colspan="3">(data OR image OR computer vision OR recognition) AND construction AND progress AND (management OR track OR monitor)</td></tr>
<tr><td>achievement</td><td colspan="3">3.600 total papers viewed</td></tr>
</table>

Within the scope of the research method followed, ScienceDirect, ASCE and Taylor & Francis online databases were searched separately with the keywords specified in Table 1. The studies published between 2017 and 2024 were filtered and the first 100 articles displayed in each search result were displayed without exception. In order to ensure that the search results were valid on the submission date, all searches were repeated to ensure that the articles obtained were up-to-date.

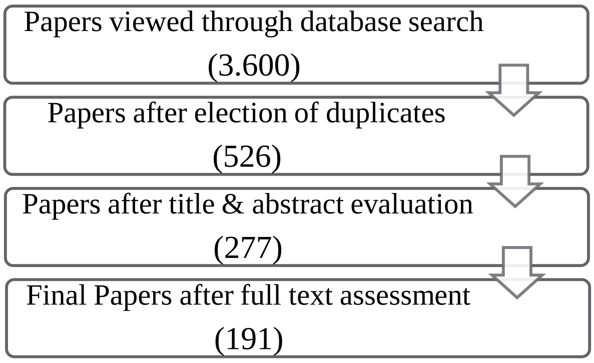

Figure 1: Literature review process.

As a result of the elimination of duplicates, the total number of articles viewed reduced from 3,600 to 526. In the next filtering step, the abstracts and titles of all articles were examined, and at this stage, although they appeared in the search results with the keyword, the works that were not related to digitalization in the CPM field were excluded from the scope of the research. In the last selection step, all texts of the articles were reviewed, and at this phase, although the articles were specifically in the field of construction site monitoring, the articles approaching the subject from different perspectives such as occupational safety, progress payment, etc. were excluded from the scope. As a result, 191 articles were chosen to be analyzed in depth and a systematic literature review was resumed.

Results

The findings obtained from the systematic review are presented in this section. Firstly, the keywords preferred by the authors and then the years of publication of the articles were analyzed. Then, the contributions of the articles to the literature were categorized according to the approach they chose and these categories were detailed. Authors used keywords in 135 of the 191 articles included within the scope of the research. All of the keywords of these 135 articles were analyzed, and the keywords repeated at least 4 or more times are presented in Table 2.

Table 2. Frequency of the keywords used by the authors in the reviewed publications.

Ranking	**Keyword**	**Count**	**Ranking**	**Keyword**	**Count**
1	Deep Learning	26	12	Automation	7
2	BIM	19	13	Construction Management	6
3	Computer Vision	17	14	Construction	6
4	Const. Prog. Monitoring	13	15	UAV	6
5	Progress Monitoring	12	16	Monitoring	5
6	Point Cloud(s)	11	17	Activity Analysis	4
7	Object Detection	10	18	Action Recognition	4
8	Construction Site	9	19	Construction Monitoring	4
9	Machine Learning	9	20	Semantic Segmentation	4
10	Photogrammetry	8	21	Productivity	4
11	Activity Recognition	8	22	Image Processing	4

As it can be seen in the Table 2, in the studies conducted in the field of digitalization of construction progress management, concepts related to artificial intelligence were used at high frequency in the literature reviewed.

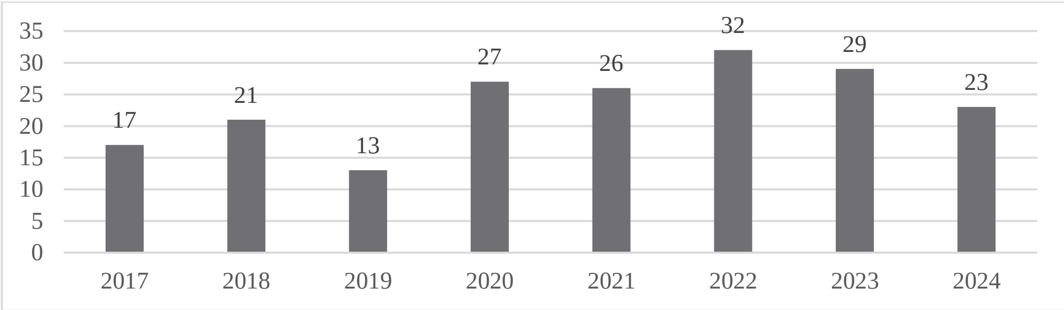

Figure 2: Number of publications based on their publication year.

The articles reviewed in this study were selected from those published between 2017-2024. An increase in the number of studies on the digitalization of CPM were observed especially in the 5 years after 2019 (Figure 2). While the average annual number of works was 17 in the 3-year period 2017-2019, this average risen up to 27.4 in the 5-year period 2020-2024, with an average increase of approximately 61%. After performing all filtering, it was seen that the 191 papers obtained can be evaluated under 3 different headings in the first phase. The categories of studies in the CPM field and the total quantity of articles (in brackets) in all relevant categories are given in Figure 3.

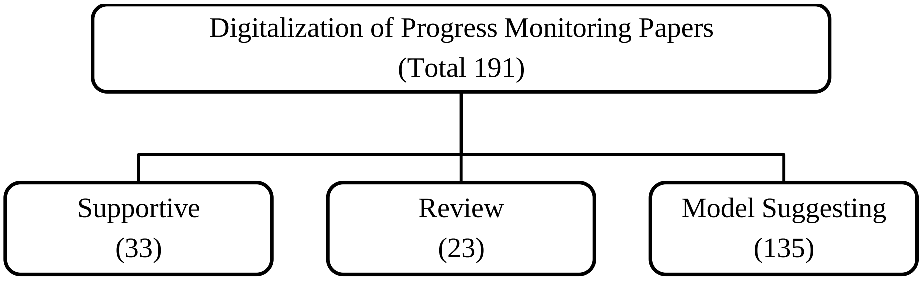

Figure 3: Classification of publications.

Supportive Studies

Studies evaluated under supportive category do not directly introduce or test a progress monitoring approach. Instead, they generate and suggest assistance for such studies and open the way for more successful implementations to be developed by the literature. 33 of the reviewed studies are listed in supportive category. To illustrate, Angah and Chen (2020) introduced a deep learning model to remove hindering objects that prevent a reasonable evaluation from the image obtained from construction site and replace the area with relevant texture that assissts for generation of a clean view. Ham and Kamari (2019) aimed for filtering construction related photographs among a gallery including higher number of varied photographs which may contribute reduce the time allocated for getting aware of as is situation.

Rashid and Louis (2019) suggested a RNN based neural network methodology to track equipment activities to contribute construction activity monitoring studies. Another example is

Xuehui et al. (2021) which collected and provided dataset for deep learning studies that focus on dynamic objects. Similarly, a dataset generated by Xiao and Kang (2021) aimed for assisting studies that are oriented CPM over machine and equipment tracking. Lee et al. (2022) employed image processing technology for CPM by creating synthetic image dataset development for equipment detection.

Review Studies

There are 23 image based review studies published in CPM field that covers the topic from different perspectives. Wang and Kim (2019) noted progress tracking as one of the main usage areas for 3D point cloud data in their comprehensive review study among model reconstruction, quality inspection, safety management etc. Zhong et al. (2019) focused on computer vision technologies and its implementations in construction practice by addressing performance analysis as one of the major fields that computer vision is employed.

Literature also interested in data gathering methods for progress monitoring in construction as Reja et al. (2022) conducted a comprehensive review and categorization study that specifically focuses on computer vision-based CPM papers. Close-range finding and data gathering methods also investigated by literature as Alaloul et al. (2021) compiled and listed opportunities and disadvantages of technologies and tools such as laser scanner, photogrammetry etc. Most of the reviewed studies (e.g. Ekanayake et al., 2021) concentrate more on image processing and computer vision related progress monitoring in construction.

Model Suggesting Studies

Of the three main categories created within the methodology of the study, the model suggesting title has the highest number of articles. A total of 135 studies were collected under this heading. Potential contributions of automated progress monitoring are being understood and studied widely by the academia. A great number of works employed various methodologies for site tracking technologies to be used for diversified areas of construction. Progress monitoring field has witnessed important developments with the contribution of sophisticated information technologies, geo-spatial 3D imaging and augmented reality fields (Omar & Nehdi, 2016). Construction management areas as efficiency analysis, quality and resources management and progress activity tracking procedures gained advantages of automated data gathering and source location surveying mechanisms (Akhavian & Behzadan, 2012).

Although digitalization of CPM is a sufficiently narrow research area, articles (e.g. Alsakka et al., 2023) with different approaches have been written and presented in the literature even in specific limited databases. Researchers (e.g. Angah & Chen, 2020) have addressed the contributions that can be made to the subject from very different perspectives. This situation can be taken as an indicator of openness of the field to further development. When the studies proposing models are analyzed in depth, it is seen that they differ significantly in their data collection and processing models and methods. While some studies (e.g. Alsakka et al., 2023) focus on a certain & specific area of the CI, some of them (e.g. Shi et al., 2024) approach the issue from a broader perspective and some of them (e.g. Chen et al., 2020) develop methods on specific input issues.

Discussion

This research study, in which papers that prioritize digitalization in the field of CPM were reviewed, basically reached the mapping in a way that would facilitate the understanding of the articles written in the area. Although the main objective was to obtain information about the studies developing models and to explore the gaps in the literature in this field, review and supportive studies were also included in the mapping.

Looking at the review studies from the top scale, it can be seen that there are many studies specializing in different perspectives. To illustrate, Puri and Turkan (2018) investigated progress monitoring of transportation construction projects specifically whereas Sherafat et al. (2020) focused on activity recognition of workers and their equipment while creating a review study. In addition to the ones mentioned in this article, it is likely that specialised review studies will be conducted in different fields based on the diversity of studies proposing models. Therefore, it is possible that review studies in the field of CPM may be diversified and presented to the literature by researchers.

Although supportive studies do not directly propose or validate a new model, they may have the effect of enhancing the performance of model-proposing studies thanks to the many improvements they suggest (e.g. Xiao & Kang, 2021) in different areas. In addition, supportive studies that provide data sets for artificial intelligence studies, create synthetic sets, provide findings that facilitate object recognition of artificial intelligence, etc. (e.g. Lee et al., 2022) certainly have the potential to provide a basis for more novel and original studies that propose models in the field of CPM. Many new, model-suggesting studies can be inspired by following the supportive studies. These studies serve as a foundation for exploring novel avenues of inquiry and expanding the existing knowledge base in various fields of study.

Among the three main categorization headings presented in this research, the last category, which includes studies proposing models, is undoubtedly the one with the widest scope. This group, which includes 135 studies in total, consists of articles that aim to digitize and automate the CPM field with different approaches. These studies differ in terms of data collection, data processing, the specific construction area they focus on and the main construction inputs they consider. When these studies are analyzed in more depth, it is possible to evaluate them in different categories under these four headings. In addition to this evaluation, more preferred fields of study and combinations can be revealed by the literature, as well as gaps that have not yet been fully analyzed.

Conclusion

This study has categorized digitalization studies in the construction progress management field in a wide range, evaluated and mapped the issues covered by the relevant studies from different fields. Three different databases were searched for studies on digitalization in the field of CPM. As a result of this search, it was revealed that there are three main categories of studies. The first category includes supportive studies, when the second includes review studies, and the third category includes model suggesting studies. Model suggesting studies, which have the highest number of studies among these three categories, differ in terms of data collection method, data processing method, specific construction area and input sources. When these areas are evaluated together, it is concluded that it can be possible for researchers to carry out studies that have not yet been included in the literature with variable preferences to be made in different categories. This study can contribute to progress monitoring researches in the field of civil engineering, architecture and interior architecture especially for construction and finishing works.

References

Alaloul, W. S., Qureshi, A. H., Musarat, M. A., & Saad, S. (2021). Evolution of close-range detection and data acquisition technologies towards automation in construction progress monitoring. *Journal of Building Engineering*, *43*, 102877.

Alsakka, F., Assaf, S., El-Chami, I., & Al-Hussein, M. (2023). Computer vision applications in offsite construction. *Automation in Construction*, *154*, 104980.

Angah, O., & Chen, A. Y. (2020). Removal of occluding construction workers in job site image data using U-Net based context encoders. *Automation in Construction*, *119*, 103332.

Chen, C., Zhu, Z., & Hammad, A. (2020). Automated excavators activity recognition and productivity analysis from construction site surveillance videos. *Automation in construction*, *110*, 103045.

Ekanayake, B., Wong, J. K. W., Fini, A. A. F., & Smith, P. (2021). Computer vision-based interior construction progress monitoring: A literature review and future research directions. *Automation in Construction*, *127*, 103705.

Ham, Y., & Kamari, M. (2019). Automated content-based filtering for enhanced vision-based documentation in construction toward exploiting big visual data from drones. *Automation in Construction*, *105*, 102831.

Kopsida, M., & Brilakis, I. (2020). Real-time volume-to-plane comparison for mixed reality–based progress monitoring. *Journal of Computing in Civil Engineering*, *34*(4), 04020016.

Lee, J. G., Hwang, J., Chi, S., & Seo, J. (2022). Synthetic image dataset development for vision-based construction equipment detection. *Journal of Computing in Civil Engineering*, *36*(5), 04022020.

Meisels, M. (2020). *2020 Engineering and construction industry outlook*. Deloitte Development LLC. https://www2.deloitte.com/content/dam/Deloitte/br/Documents/energy-resources/Deloitte-2020-engineering-construction-industry-outlook.pdf.

Nahangi, M., & Haas, C. T. (2014). Automated 3D compliance checking in pipe spool fabrication. *Advanced Engineering Informatics*, *28*(4), 360-369.

Omar, T., & Nehdi, M. L. (2016). Data acquisition technologies for construction progress tracking. *Automation in Construction*, *70*, 143-155.

Puri, N., & Turkan, Y. (2018). A review of technology supplemented progress monitoring techniques for transportation construction projects. In *Construction Research Congress* 2018 (pp. 512-521).

Rashid, K. M., & Louis, J. (2019). Times-series data augmentation and deep learning for construction equipment activity recognition. *Advanced Engineering Informatics*, *42*, 100944.

Reja, V. K., Varghese, K., & Ha, Q. P. (2022). Computer vision-based construction progress monitoring. *Automation in Construction, 138*, 104245.

Ribeirinho, M., Mischke, J., Strube, G., Sjödin, E., Blanco, J., Palter, R., Biörck, J., Rockhill, D., & Andersson, T. (2020). The next normal in construction. *Mckinsey & Company IOP Pub*, 1, 012011.

Sherafat, B., Ahn, C. R., Akhavian, R., Behzadan, A. H., Golparvar-Fard, M., Kim, H., Lee, Y. C., Rashidi, A., & Azar, E. R. (2020). Automated methods for activity recognition of construction workers and equipment: State-of-the-art review. *Journal of Construction Engineering and Management*, *146*(6), 03120002.

Shi, M., Chen, C., Xiao, B., & Seo, J. (2024). Vision-based detection method for construction site monitoring by integrating data augmentation and semisupervised learning. *Journal of Construction Engineering and Management*, *150*(5), 04024027.

Wang, Q., & Kim, M. K. (2019). Applications of 3D point cloud data in the construction industry: A fifteen-year review from 2004 to 2018. *Advanced Engineering Informatics*, *39*, 306-319.

Xiao, B., & Kang, S. C. (2021). Development of an image data set of construction machines for deep learning object detection. *Journal of Computing in Civil Engineering*, *35*(2), 05020005.

Xuehui, A., Li, Z., Zuguang, L., Chengzhi, W., Pengfei, L., & Zhiwei, L. (2021). Dataset and benchmark for detecting moving objects in construction sites. *Automation in Construction*, *122*, 103482.

Zhang, C., Shen, W., & Ye, Z. (2022). Technical feasibility analysis on applying ultra-wide band technology in construction progress monitoring. *International Journal of Construction Management*, *22*(15), 2951-2965.

Zhong, B., Wu, H., Ding, L., Love, P. E., Li, H., Luo, H., & Jiao, L. (2019). Mapping computer vision research in construction: Developments, knowledge gaps and implications for research. *Automation in Construction*, *107*, 102919.

Using ChatGPT for Risk Management in Construction Industry: A Literature Review

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Abstract

One of the most promising developments in artificial intelligence (AI) is the emergence of ChatGPT (Generative Pre-trained Transformer), a powerful language model developed by OpenAI. Despite its broad adoption across various sectors, the application of ChatGPT within the construction industry, particularly for country risk assessment in project management, remains significantly underexplored. To fully understand ChatGPT's potential in country risk management, it is essential to first evaluate its performance for this specific purpose, identifying both its limitations and capabilities. Currently, there is no study that investigates the use of ChatGPT specifically for country risk management in construction projects, although there are studies on its application in general risk management. This paper critically reviews the existing literature to identify gaps, focusing specifically on the integration and application of ChatGPT in risk management. It discusses current methodologies and the findings reported across these studies, proposes a methodological framework for evaluating ChatGPT's performance in real-world scenarios for country risk assessment, and identifies key deficiencies and potential research directions. This paper lays the groundwork for future studies aimed at enhancing the efficacy of ChatGPT in country risk assessment within construction project management. This research is pivotal for understanding how ChatGPT can be optimized to improve risk management practices, ensuring more effective and informed decision-making in the construction industry.

Keywords: *Artificial intelligence, ChatGPT, country risk assessment, generative AI, international construction, risk management.*

Introduction

ChatGPT is increasingly utilized across various industries, including healthcare, programming, media and entertainment, education, finance, sales and marketing, and customer service, showing remarkable potential in transforming these fields (McKinsey, 2022; Bain, 2024). Despite its widespread adoption, the use of ChatGPT within the construction sector, specifically in risk management, remains limited.

Given the significant impact of country risks on construction projects, it is essential to evaluate ChatGPT's performance in country/political risk identification and assessment. This evaluation will help understand its potential and identify its limitations. Notably, there is a lack of studies focusing on the evaluation of ChatGPT for country risk assessment in the construction industry.

This study reviews existing studies on the use of ChatGPT in country risk assessment for construction project management and aims to bridge the gap in the literature by investigating how its performance can be effectively evaluated in these risk assessment processes. The initial phase of this study involves a comprehensive literature review to understand the current state of AI applications, specifically ChatGPT, in the construction sector with a focus on risk management. This review highlights a significant research gap in the application of ChatGPT for managing country-specific risks, which are crucial for project success. Following the literature review, this paper proposes potential methods for evaluating ChatGPT's performance in country risk assessment processes to facilitate risk management in construction projects. By discussing the limitations and opportunities identified in our review, this research outlines prospects for future studies and practical implementations that could significantly advance the field.

Literature Review

This section reviews previous studies to understand the development and integration of AI in the field of risk management within the construction industry. Exploring these studies provides a contextual background to our current examination of ChatGPT's potential in country/political risk assessment, setting the stage for understanding how AI's capabilities and applications have been evaluated and adopted in similar contexts.

Building on the recent advancements in AI, studies have begun to focus towards safety risk management within the construction sector. Abioye et al. (2021) reviewed the adoption of artificial intelligence (AI) in the construction industry, which is notably slower compared to industries like manufacturing, despite AI's potential to enhance efficiency, safety, and profitability. The research focused on key AI technologies such as machine learning, computer vision, and robotics, and their applications in monitoring, risk management, and resource optimization. The study further discussed how integrating various digital technologies, including IoT sensors, UAVs, wearable devices, and BIM, plays a crucial role in preventing and mitigating safety risks at different stages of construction.

In a similar study, Kamari and Ham (2022) developed an AI-based risk assessment framework utilizing deep learning and digital twinning to enhance disaster preparedness on construction sites against hurricanes. The researchers focused on construction sites due to their high vulnerability to extreme wind events, which can transform unsecured materials into dangerous projectiles. By implementing a vision-based digital twinning system, they were able to predict and map the risk posed by potential wind-borne debris more efficiently and accurately. This allowed construction site managers to implement more effective hurricane preparedness plans, minimizing potential damages to the infrastructure and surrounding areas.

With the development of conversational AI, there has been a notable shift towards leveraging chatbots and other AI-driven tools for various applications. For instance, ChatGPT has emerged as a significant player in this space, potentially transforming risk management processes. In parallel, studies have begun to evaluate the use of ChatGPT in risk management. Some of these assessments in the literature relied on expert opinions to measure AI performance, while others were based on empirical data without expert intervention.

Barcaui and Monat (2023) presented a comparison between generative AI, particularly GPT-4, and human project managers in developing project plans within the digital technology sector. The study employed a primarily qualitative methodology to assess critical aspects of project planning such as scope, schedule, cost, resources, and risk management, and evaluated risk management strategies in project plans created by a generative AI system and a human project manager. According to the results, the AI-generated risk plan was comprehensive, covering risk identification, assessment, and response across various domains like legal, technological, and financial risks. It included qualitative and quantitative assessments, enabling focused risk prioritization and detailed response strategies. On the other hand, the human-generated plan primarily focused on identifying risks without a detailed framework for assessing or managing them, lacking categorization and specific response strategies. This made it less effective at preparing the project team for potential challenges. In contrast, the AI's structured approach significantly enhanced the project's ability to manage risks effectively. Overall, the AI-generated risk plan demonstrated a rigorous and structured approach to risk management, substantially improving the project's likelihood of success. In addition, the study highlighted the importance of synergy between human experience and AI in project management, recommending an integrated approach for robust and effective project planning.

Klepo et al. (2023) utilized ChatGPT to evaluate risk response strategies and highlight its capabilities and limitations. The researchers focused on identifying and analyzing significant risks by project managers (PMs) and comparing risk response strategies proposed by project managers PMs and AI. As an AI tool, the authors utilized OpenAI's ChatGPT 3.5 version. The research utilized a risk matrix model specific to water infrastructure to categorize risks and response strategies, finding that AI can significantly enhance the efficiency of risk management by quickly identifying potential risks and suggesting effective mitigation strategies. However, the study also emphasized the necessity of human oversight in decision-making processes to address the limitations of AI, such as context understanding and the need for high-quality data inputs. The overlap between PM and AI-generated strategies was approximately 52%, demonstrating AI's potential as a supportive tool rather than a replacement for human expertise in managing project risks.

One of the unique studies that assessed the capabilities of ChatGPT used a conversational methodology to explore its effectiveness in quantitative risk management. Hofert (2023) evaluated the effectiveness of GPT-3.5 in understanding and executing tasks related to quantitative risk management. The paper employed a conversational methodology to assess the capabilities of GPT-3.5. The AI was posed with various risk management-related questions, and its responses were analyzed for accuracy and depth of understanding. The questions covered risk definitions, risk types, and detailed scenarios like the 2007-2009 financial crisis, exploring the AI's ability to handle both theoretical and practical aspects of risk management. The study revealed several key points: ChatGPT struggles with precise mathematical queries, often producing convincing yet incorrect answers due to its predictive nature. It occasionally misinterprets nuanced questions, leading to errors underlining the importance of careful question framing. The model's static knowledge base prevents real-time updates, causing the repetition of inaccuracies and limiting its educational efficacy. Despite these limitations, ChatGPT strengthens in summarizing documented topics, facilitating broad understanding and discussion, thus potentially enhancing critical thinking and analytical skills in educational contexts. It also supports developing one's own knowledge of quantitative risk management and is an inspiring tool in creative and informal learning environments.

There are also studies that assess the results of using ChatGPT in risk management with the involvement of experts. These studies highlight the nuanced capabilities of ChatGPT in facilitating risk management processes while emphasizing the need for expert oversight. The research by Aladağ (2023) assessed the accuracy of using ChatGPT for risk management in construction projects. It identified that while AI, specifically ChatGPT, has been recognized for its potential to enhance decision-making within risk management, its performance is only moderate. The study evaluated ChatGPT's capabilities in handling various risk management sub-processes such as risk identification, analysis, response, and monitoring. The research methodology involved determining Key Performance Indicators (KPIs) for each risk management sub-process, preparing a questionnaire based on these KPIs, and then collecting data from ChatGPT. The data collected from ChatGPT were evaluated using expert focus group sessions. This method allowed for assessing ChatGPT's accuracy in risk identification, analysis, response, and monitoring in various construction project types. The author of this study utilized ChatGPT-4 (ChatGPT Demo) for gathering data. According to the findings of this study, ChatGPT demonstrated moderate performance across various risk management sub-processes, with particular strengths in risk response and monitoring. However, it was less effective in risk identification and analysis. Expert evaluations revealed that while ChatGPT can generate a broad range of risk factors and responses, its accuracy and relevance in connecting and prioritizing these risks are limited. The study underscored the need for supplementary human expertise to interpret and adapt AI-generated information for practical, context-specific applications in construction risk management. This research contributes to understanding the potential and limitations of AI tools in enhancing decision-making processes within the construction industry.

Further expanding on this theme, Al-Mhdawi et al. (2023) evaluated the performance of ChatGPT in the domain of risk management based on the ISO 31000 standard by surveying construction and project risk academics in Iraq. ISO 31000 is a globally acknowledged standard for risk management that offers a detailed structure for identifying, analyzing, evaluating, addressing, monitoring, and communicating risks. In this study, the researchers pinpointed a total of 12 indicators for assessing ChatGPT's effectiveness in managing construction risks according to ISO 31000, then established the primary criteria for evaluating these indicators, and created a fuzzy-based evaluation model to quantify ChatGPT's performance by measuring the variability and significance of the identified performance indicators. ChatGPT demonstrated high effectiveness in managing project risks according to the ISO 31000 standard, mainly by providing relevant risk mitigation strategies that significantly improved outcomes. However, the study stated that exercising caution when relying solely on ChatGPT for risk assessment and prioritization is crucial, as manual review and verification remain essential for ensuring accuracy and reliability.

In a distinct approach to evaluating AI, Nyqvist et al. (2024) conducted a study on the ChatGPT-4 in construction project risk management (CPRM), comparing its performance against with 16 human risk management experts from Finnish construction companies. Their research employed a mixed-methods approach involving qualitative and quantitative assessments through anonymous peer reviews. The objective was to develop a strong assessment of risk management skills that mirrors real-life conditions. This was achieved by minimizing bias toward AI or human responses using anonymous peer evaluations. The findings indicate that ChatGPT-4 generates comprehensive risk management plans, significantly outperforming human experts in quantitative evaluations. On the exercise evaluated by human reviewers, human experts scored an average of 5.7, whereas ChatGPT achieved an average score of 8.6. That average was calculated using risk identification, risk analysis, and control based on the method offered by the authors. However, despite its superior data processing abilities, the AI's risk management strategies lacked practicality and specificity, areas where human experts showed better performance. This study underscored the potential for AI to augment human capabilities in CPRM, recommending a collaborative approach where AI serves as an augmentative tool, enhancing the efficacy of human decision-making in risk management.

In their very recent study, Yazdi et al., (2024) provided a responsive analysis of artificial intelligence (AI) applications in risk management, contrasting AI-enhanced methods with traditional approaches and discussing the emerging challenges and opportunities. The authors explored how AI, particularly deep learning and convolutional neural networks, can be leveraged to enhance risk assessment processes by enabling more accurate and timely insights. They highlighted the importance of integrating AI with domain-specific expertise to overcome AI's limitations in contextual interpretation. The comparative analysis was based on case studies that illustrate AI's capacity to significantly improve the efficiency and efficacy of risk assessments in diverse industries. The research underlined the transformative potential of AI in risk management, advocating for ongoing research to optimize its integration into existing frameworks.

As a comprehensive evaluation of GPT models in the construction industry, Saka et al. (2024) discussed the application of these models for managing construction risks and enhancing project management. Utilizing a qualitative approach, the research aimed to critically evaluate the use of GPT models, focusing on identifying opportunities, assessing limitations, and validating use cases. The study found that GPT models offer significant potential to improve aspects of the construction industry such as project management, risk assessment, and resource optimization. However, it also highlighted several challenges, including the need for clean data, integration complexities, and the industry's slow adoption rate. The use case validation demonstrated the practical utility of GPT models, showcasing their ability to enhance decision-making and operational efficiency in construction projects. Although comprehensive, the study did not address the use of ChatGPT for country risk assessment.

Ghimire et al. (2024) provided an extensive examination of the opportunities and challenges associated with the adoption of generative AI technologies in the construction industry. They explored the impact of these technologies on project efficiency, safety management, cost predictions, and overall decision-making processes. According to this study, the integration of Generative AI (GenAI) in the construction industry presents both opportunities and challenges. The authors discussed the complexities of domain knowledge integration and the need for continuous model updating and interpretability in the context of project management. The potential for GenAI to automate risk analysis and generate optimal schedule paths was discussed as part of a broader effort to increase efficiency and accuracy in project management within the construction industry. The study also highlighted significant gaps in current research, particularly the lack of studies on the integration of generative AI within the industry's unique operational contexts. The paper concluded by proposing a conceptual framework for implementing generative AI in construction, aiming to enhance practical applications and encourage further research. While this paper provides a broad perspective on the application of generative AI in construction, it does not encompass the specific area of country risk assessment.

Discussion of Findings

The literature reviewed reveals a number of studies exploring the application of ChatGPT in risk management, primarily within the construction industry. This discussion synthesizes the methodologies used and the findings reported across these studies, providing an overview of the current state of AI in managing risks.

The methodological diversity among the studies ranges from qualitative and mixed methods to empirical and comparative analyses. Barcaui and Monat (2023) employed a qualitative methodology to compare AI-generated project plans with those of human project managers in project plan development. Hofert (2023) adopted a conversational methodology to evaluate ChatGPT's performance in quantitative risk management, offering a nuanced analysis of AI's capabilities and limitations. On the other hand, Klepo et al. (2023) explored the use of ChatGPT in evaluating risk response strategies by comparing it to traditional human analysis, utilizing a risk matrix model to categorize and evaluate responses. Aladağ (2023) and Al-Mhdawi et al. (2023) both integrated expert opinions to evaluate ChatGPT's performance; the former focused on assessing ChatGPT's accuracy in risk management within construction projects, while the latter examined its effectiveness based on the ISO 31000 standard. In another study, Nyqvist et al. (2024) employed a unique mixed-methods approach involving anonymous peer reviews to compare the performance of ChatGPT with human experts, emphasizing a strong comparative basis to mirror real-life conditions.

The reviewed literature indicates that while ChatGPT can significantly enhance risk management processes, it also has notable limitations. Most studies have revealed both strengths and weaknesses of AI in risk management. For example, Aladağ (2023) found moderate performance in ChatGPT's ability to handle risk management tasks, with particular strengths in response and monitoring, yet noted limitations in risk identification and analysis. Hofert (2023) explored ChatGPT's effectiveness in quantitative risk management, pointing out the model's limitations in handling precise mathematical queries, although it was successful in the non-technical aspects of risk. Similarly, Nyqvist et al. (2024) found that ChatGPT outperformed humans in quantitative evaluations but lacked practicality and specificity, indicating a need for enhancement in practical risk management applications.

The need for human oversight was consistently emphasized across studies to address AI's limitations in context understanding and real-time data processing. Al-Mhdawi et al. (2023) demonstrated high effectiveness of ChatGPT in managing project risks according to ISO 31000 standards although it emphasized the necessity for manual review to ensure accuracy. Similarly, Klepo et al. (2023) highlighted AI's capability to quickly identify risks and propose strategies thereby illustrating AI's utility in augmenting efficiency in risk management. However, it emphasized the human endeavour needed in assessment of suitability and implementation of them within the given context. Barcaui and Monat (2023) said that Generative AI can help with project management knowledge areas, at the same time, found that both AI-generated and human-generated project plans have unique strengths and weaknesses, suggesting a collaborative approach may be optimal, emphasizing the continued importance of human expertise in refining AI outputs.

This literature review and discussion underscore both the transformative potential and the limitations of AI in construction risk management. The literature highlights AI's potential and the importance of integrating it into the risk management process. However, it also points to the necessity of augmenting AI with human expertise to address its weaknesses when necessary.

The current literature reveals a lack of studies specifically evaluating the use of ChatGPT for country/political risk management. Moreover, research examining the role of ChatGPT in risk management processes, particularly through interactive studies involving experts and hands-on sessions, is scarce. In light of this literature review, it becomes crucial to focus specifically on studies related to country risk assessment using ChatGPT. Such research should aim to identify opportunities and limitations, evaluate ChatGPT's performance in current and potential applications through expert opinions, and comprehensively discuss its potential impacts.

Moreover, existing research in the risk management domain using both earlier models (i.e., GPT-3.5) and more advanced ones (i.e., GPT-4) indicates that older models often exhibited critical errors, such as failing to adjust responses appropriately despite changes in the country or region specified in the prompts. Therefore, assessing the performance of the latest version, ChatGPT-4, in political risk identification and assessment is crucial for its potential adoption in the construction industry.

Conclusions

The rapid advances in AI and subsequent developments in tools like ChatGPT have accelerated their adoption across various sectors. However, as with many technological innovations, the unique characteristics of the construction industry have delayed the integration of such technologies in this field. Similarly, research specifically focusing on the application of ChatGPT in country risk assessment within construction remains limited and largely unexplored.

This study illuminates the critical need for ongoing research to refine AI applications, so that these technologies may be effectively tailored to meet the specific demands and challenges of the construction industry. Given the gaps identified in country-specific risk assessment, focused studies on the application of ChatGPT and similar AI tools in country risk identification and assessment within the construction sector are imperative. These studies should comprehensively explore AI's performance, taking into account the dynamic and complex nature of country risks, and develop methodologies that incorporate both expert opinion and empirical data for a balanced and in-depth evaluation of AI’s capabilities and limitations.

To effectively integrate ChatGPT into construction project risk management, especially for country risk assessment, focused research involving collaborations with risk management experts is essential. These experts can help develop and refine prompts that accurately reflect the industry's real-world complexities and specific challenges. Future studies should explore how ChatGPT handles dynamic political landscapes, identifies subtle yet significant geopolitical risks, and adjusts its responses based on regional variations through real-world case studies and pilot projects.

In evaluating the performance of ChatGPT for use in construction project management, particularly for country risk assessment and identification, it is crucial to incorporate interactive studies emphasizing the significance of expert-designed prompts. These sessions should allow industry experts to directly input and refine prompts, enabling a real-time understanding of how ChatGPT processes complex industry-specific information under practical conditions. This hands-on approach ensures that the AI's responses are not only tested in theoretical scenarios but are also examined under practical conditions reflective of real-world complexities.

In addition, constructing comprehensive evaluation frameworks will be crucial, allowing researchers to benchmark ChatGPT's performance against historical data and expert assessments to ensure consistency and reliability in evaluations. Training sessions may be conducted to equip construction professionals with the skills to effectively utilize and interpret AI tools, fostering an environment of continuous feedback and adaptation.

In the future, the authors' plans include establishing focus groups of industry experts experienced in risk management to discuss further the potential use of ChatGPT for country risk assessment in the construction sector and test ChatGPT's capabilities in managing country risks through interactive applications involving hypothetical or real-world scenarios, designed to thoroughly test ChatGPT's capabilities in this specific context. The process will involve expert-driven prompt creation and subsequent evaluation of ChatGPT's responses to these prompts. The gathered data from these interactive sessions will be analyzed to assess the performance of ChatGPT, offering valuable insights into its practical effectiveness and areas for enhancement. This structured approach will ensure that the findings are grounded in the practical realities of the construction industry, offering a robust framework for understanding how AI can contribute to more advanced and nuanced risk assessment strategies. Ultimately, this planned research aims to not only illuminate the limitations of ChatGPT but also lead or contribute to future improvements better to meet the specialized demands of country risk management.

In conclusion, this paper has explored the potential applications of ChatGPT in the construction industry, with a particular focus on risk management, including country risk assessment. It has highlighted the benefits of employing ChatGPT for these purposes and also identified broader opportunities to harness this technology in various aspects of construction project management. By expanding the scope of AI applications like ChatGPT within the construction industry, we can leverage AI to overcome traditional challenges in the following areas:

Comprehensive Project Risk Management: ChatGPT can be effectively utilized to facilitate a holistic approach to identifying, analyzing, and mitigating potential risks across different project stages.
Project Planning and Scheduling: ChatGPT can assist in the planning and scheduling phases by generating and evaluating potential project timelines and milestones.
Regulatory Adherence: With its extensive knowledge base, ChatGPT can help ensure compliance with both local and international construction regulations. It can track updates in regulatory frameworks and advise on compliance strategies, thereby reducing the risk of non-compliance penalties.

By enhancing these areas, ChatGPT can offer unique opportunities to improve efficiency and decision-making in the construction industry. We emphasize the necessity for further empirical and practical research into the rapidly-developing capabilities of ChatGPT. Moving forward, ongoing research is essential to examine how ChatGPT can be further utilized, especially in fields where significant gaps remain, such as country risk assessment.

References

Abioye, S. O., Oyedele, L. O., Akanbi, L., Ajayi, A., Delgado, J. M. D., Bilal, M., Akinade, O. O., & Ahmed, A. (2021). Artificial intelligence in the construction industry: A review of present status, opportunities and future challenges. *Journal of Building Engineering, 44*, 103299. https://doi.org/10.1016/j.jobe.2021.103299

Aladağ, H. (2023). Assessing the Accuracy of ChatGPT Use for Risk Management in Construction Projects. *Sustainability*, 15(22), 16071. https://doi.org/10.3390/su152216071

Al-Mhdawi, M. K. S., Qazi, A., Alzarrad, A., Dacre, N., Rahimian, F. P., Buniya, M. K., & Zhang, H. (2023). Expert Evaluation of ChatGPT Performance for Risk Management Process based on ISO 31000 Standard. *33rd European Safety and Reliability Conference, ESREL*, 2529–2533. https://doi.org/10.3850/978-981-18-8071-1_p733-cd

Bain (2024). *OpenAI Alliance*. https://www.bain.com/vector-digital/partnerships-alliance-ecosystem/openai-alliance/ accessed: 01 May 2024

Barcaui, A., & Monat, A. (2023). Who is better in project planning? Generative artificial intelligence or project managers? *Project Leadership and Society*, 4. https://doi.org/10.1016/j.plas.2023.100101

Ghimire, P., Kim, K., & Acharya, M. (2024). Opportunities and Challenges of Generative AI in Construction Industry: Focusing on Adoption of Text-Based Models. *Buildings*, 14(1), 220.

Hofert, M. (2023). Assessing ChatGPT's Proficiency in Quantitative Risk Management. *Risks*, 11(9), 166. https://doi.org/https://doi.org/10.3390/risks11090166

Kamari, M., & Ham, Y. (2022). AI-based risk assessment for construction site disaster preparedness through deep learning-based digital twinning. *Automation in Construction*, 134, 104091. https://doi.org/10.1016/j.autcon.2021.104091

Klepo, M. S., Knežević, D., Knežević, T., & Meštrović, H. (2023). Artificial Intelligence in Risk Management System on Infrastructure Projects. *Proceedings of the Creative Construction Conference*, June, 208–214. https://doi.org/10.3311/ccc2023-028

McKinsey (2022). *Generative AI is here: How tools like ChatGPT could change your business.*https://www.mckinsey.com/capabilities/quantumblack/our-insights/generative-ai-is-here-how-tools-like-chatgpt-could-change-your-business accessed: 01 May 2024

Nyqvist, R., Peltokorpi, A., & Seppänen, O. (2024). Can ChatGPT exceed humans in construction project risk management? *Engineering, Construction and Architectural Management*, 31(13), 223–243. https://doi.org/10.1108/ECAM-08-2023-0819

Saka, A., Taiwo, R., Saka, N., Salami, B. A., Ajayi, S., Akande, K., & Kazemi, H. (2023). GPT models in construction industry: Opportunities, limitations, and a use case validation. *Developments in the Built Environment*, 100300.

Yazdi, M., Zarei, E., Adumene, S., & Beheshti, A. (2024). Navigating the Power of Artificial Intelligence in Risk Management: A Comparative Analysis. *Safety*, 1–48.

A Decision-support System for Resource Leveling

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Abstract

Fluctuations in resource usage pose a challenge in resource management as such fluctuations can result in decreased labor efficiency, extended project duration, and increased project cost. Resource leveling, which is one of the two most prevalent approaches for resource management, is designed to minimize fluctuations in resource usage while maintaining the project duration and resource requirements constant. The literature review on resource leveling in construction projects reveals that an objective function (e.g., minimization of the sum of the absolute deviations between resource usage for a determined time interval (day, week etc.) and the average resource usage) can be employed to achieve a leveled resource histogram. Nevertheless, different schedules may provide the same result for the objective function used to level resources. Determining the most appropriate schedule from a set of alternatives that yield the same result for the objective function used to level resources is a challenging task for schedulers. Therefore, the objective of this study is to propose an approach to select the most appropriate schedule after resource leveling in construction projects. A case study was carried out to illustrate the practical application of the proposed approach in a real-life construction project. The proposed approach assists schedulers in making decisions by using objective data in the selection of the most appropriate schedule after resource leveling, thereby resulting in enhanced resource management and improved project performance.

Keywords: *construction projects, resource leveling, resource management, scheduling.*

Introduction

The Critical Path Method (CPM) has been the most common technique employed in the scheduling of construction projects since 1950 (Lu et al., 2008). CPM assumes that there are no limitations on the availability of resources when scheduling a construction project (Senouci &

Adeli, 2001; Chen & Weng, 2009; Hariga & El- Sayegh, 2011). However, resources such as labor, equipment, and materials are limited in real-life construction projects and may need to be distributed among multiple projects. Limitations in available resources can lead to delays and budget overruns in construction projects (Damci & Polat, 2014). In complex projects, such as construction projects, where multiple activities are conducted simultaneously, the effective management of resources is crucial, because efficient allocation and utilization of resources have a positive impact on the project's success (Hariga & El- Sayegh, 2011; Damci & Polat, 2014).

In the field of construction project management, there are two basic approaches for managing resources: resource allocation and resource leveling. On the one hand, resource allocation is the process of distributing resources to activities throughout the entire duration of a project (Chilton, 2022). On the other hand, resource leveling is concerned with balancing the demand for resources with the available supply over a period of time (Erdal & Kanit, 2021). The aim of resource leveling is to smooth out resource utilization to prevent peaks and valleys in resource usage, thereby preventing over allocation or underutilization of resources (Son & Skibniewski, 1999; Leu et al., 2000; Doulabi et al., 2011; Hariga & El- Sayegh, 2011).

Research on resource leveling in construction projects has employed objective functions, such as minimizing the sum of absolute deviations between resource usage and average resource requirements at specific time intervals, in order to achieve a leveled resource usage histogram. Although objective functions are useful, it is still a difficult task for schedulers to determine the most appropriate schedule from a set of alternatives that yield the same results for the leveling objective function. While many studies have been conducted on resource leveling in the current body of knowledge, none have concentrated on identifying the most optimal schedule among multiple schedules that yield the same ideal result for the objective function used in resource leveling. Therefore, the primary objective of this study is to propose a systematic approach for selecting the most appropriate schedule after resource leveling in construction projects. A case study is carried out to illustrate how the proposed model can be practically applied to a real-life construction project. With the use of objective data, the proposed model assists schedulers in choosing the best schedule following resource leveling, which improves project performance and resource management.

The Decision-Support System for Resource Leveling

The decision support model for resource leveling was developed in a web-based environment utilizing JavaScript, HTML, and CSS. An interface that effectively visualizes and manages resources is achieved through the use of JavaScript for logic, CSS for design, and HTML for framework. The model consists of three modules: scheduling module, resource leveling module, and decision making module. The following subsections describe the objectives, contents, and functions of each module.

Scheduling Module

The scheduling module handles simple CPM calculations. The scheduling module is designed to perform the forward and backward passes in the CPM calculations. The scheduling module follows a two-step process.

Step 1: The user inputs data into the module, including activity names/codes, activity durations, predecessor-successor relationships between activities, and the daily resource requirements for each activity.

Step 2: Early start/finish times, late start/finish times and floats of activities are computed after inputting the necessary data into the module. Subsequently, the module presents comprehensive findings on the CPM network diagram, which includes the generation of the project's resource usage histogram.

The resource leveling module receives the outputs generated by the scheduling module, thereby confirming the scheduling module's function as the input provider for the resource leveling module. The resource leveling module utilizes inputs from the scheduling module to carry out its own algorithmic processes. Notably, every module is designed to run in harmony by means of interaction with one another.

Resource Leveling Module

The resource leveling module is responsible for handling the basic process of resource leveling. The objective of the resource leveling module is to optimize resource utilization by minimizing fluctuations and maintaining a consistent level of resource usage. The resource leveling module follows a two-step process.

Step 1: All potential combinations of the CPM network diagram are generated by shifting the early start times of non-critical activities within the total float durations. In addition, a resource usage histogram for every potential CPM network diagram is generated. When generating all possible CPM network diagrams, it should be noted that the precedence relationships between activities are maintained because the total float of a non-critical activity is shared with other non-critical activities on the same path.

Step 2: The result of the objective function is calculated for every CPM network diagram. The main purpose of objective functions is to improve the resource leveling process (Damci et al., 2019). According to Damci and Polat (2014), nine objective functions are utilized in the process of resource leveling in the relevant literature. Objective functions can improve the uniformity of resource use by achieving a balanced allocation of resources without changing the project duration (Popescu & Borcherding, 1975; Easa, 1989; Mattila & Abraham, 1998). The proposed model uses the objective function of minimization of the sum of the absolute deviations between resource usage for a determined time interval (day, week etc.) and the average resource usage to achieve resource leveling (Eq. 1).

$$z = min \sum_{i=1}^{T} |R_i - A_{rr}| \quad (1)$$

where i= day under consideration, T= the duration of the project, R_i = resources required on day i, A_{rr}= average resource usage.

The decision making module receives the outcomes generated by the resource leveling module, thus validating the role of the resource leveling module as the input provider for the decision making module. The decision making module runs its own algorithms using data received by the resource leveling module.

Decision Making Module

The decision making module concentrates on the procedure of making objective decisions. The decision making module is specifically designed to determine the schedule that has the lowest objective function result out of all the potential CPM network diagrams. The decision making module follows a one-step process.

Step 1: Following the computation of objective function results for all CPM network diagrams, the schedule with the lowest objective function result is determined. However, several different schedules can achieve an identical minimum result for the objective function employed to level resources. Schedulers are faced with the difficult task of identifying the optimal schedule from a set of alternatives which yield the same results with regard to the objective function used for resource leveling. In such a case, the decision making module provides to the user the schedule that maximizes the sum of the total floats of activities among multiple schedules which achieve the same minimum result for the objective function. The basic logic underlying this approach is to select the schedule that provides the greatest degree of flexibility from the schedules that exhibit the most balanced resource utilization histogram. In construction project scheduling, schedule flexibility is critical due to its influence on project success and risk mitigation. Su et al. (2015) state that total float significantly contributes to schedule flexibility by providing a measure for the degree of flexibility in scheduling activities without leading to delays in project completion. The availability of total float allows for the absorption of potential delays without impacting the overall project duration, thereby diminishing the likelihood of project delays (Tran & Long, 2018). The level of schedule flexibility in a project is directly related to the amount of total float it has. Therefore, a project with more total float inevitably has a greater degree of schedule flexibility. As a result, the decision making module objectively provides users with a schedule that has the most balanced resource utilization histogram as well as the greatest schedule flexibility. Construction professionals are better able to manage resources, adapt to changes, reduce risks, and complete projects successfully when they have a resource-balanced schedule with maximum flexibility.

An Illustrative Example of the Proposed Decision-Support System

One of the best ways to validate the applicability and effectiveness of the proposed model is to use an illustrative example. A network diagram consisting of 20 activities, which was adapted from Hegazy's (1999) study, is utilized as an example. The CPM network diagram for the example is presented in Figure 1. Figure 1 displays information for each activity, including precedence relationships, durations (in days), and daily resource requirements. The start time of the project is assumed to be "0".

The proposed decision-support system was run after the necessary data were entered. All three modules run in synchronization. When the scheduling module is run, the early start/finish times, early/late finish times, and total floats of activities are calculated (Figure 1). The resource usage histogram before resource leveling is presented in Figure 2a. The sum of the absolute values of the deviations between resource usage on any day and the average resource usage is 112 for the initial resource use histogram and the total project duration is 27 days. After generating the initial schedule and resource histogram, the scheduling module identifies non-critical activities.

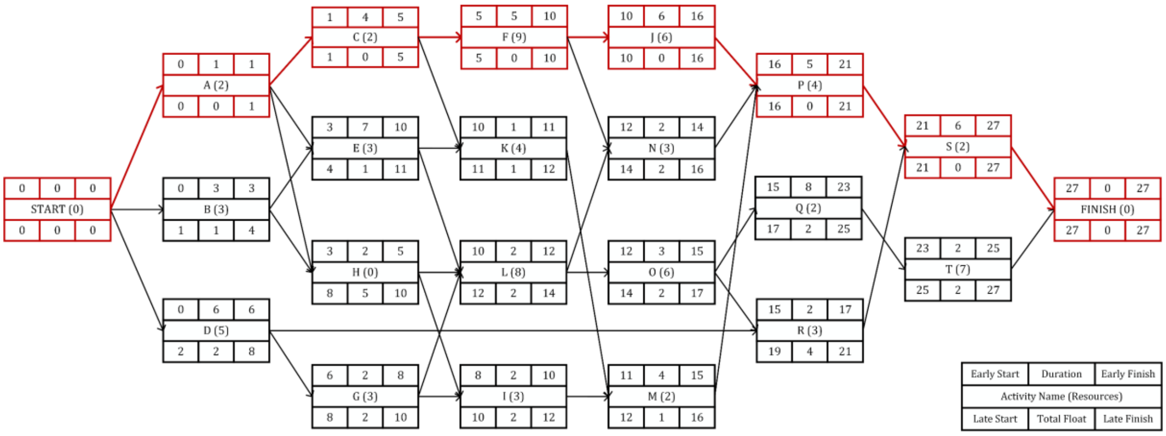

Figure 1: Initial CPM network diagram for the example project.

Following the development of the initial CPM network diagram and resource histogram, the resource leveling module runs automatically. A total of 24,971 unique schedules were generated by changing the early start times of non-critical activities, while ensuring that the dependencies between activities were not violated. Then, for each schedule, the objective function in Equation (1) is utilized to compute the sum of the absolute values of the deviations between the resource utilization on any given day and the average resource utilization. According to the outcomes of the resource leveling module, there are 20 different objective function results for all schedules.

Ultimately, the decision-making module selects the schedule or schedules that yield the lowest outcome out of 20 distinct objective function results. The lowest result of the objective function was determined to be 90 labor/day. Upon analyzing the results, the decision-making module determined that 348 out of 24,971 schedules provided the minimum objective function result. It was noted that some schedules out of a total of 348 exhibited varying sum of total floats. Table 1 presents the frequencies of the sum of the total floats of the 348 schedules. Based on the data in Table 1, there is only one schedule that offers the highest level of flexibility (i.e., 21 days of total float) while also achieving the lowest objective function result (i.e., 90 labor/day) for resource leveling. The resource utilization histogram obtained after the resource leveling procedure for this schedule is presented in Figure 2b. Figure 3 shows the CPM network diagram of the schedule that has the highest level of flexibility after the resource leveling procedure.

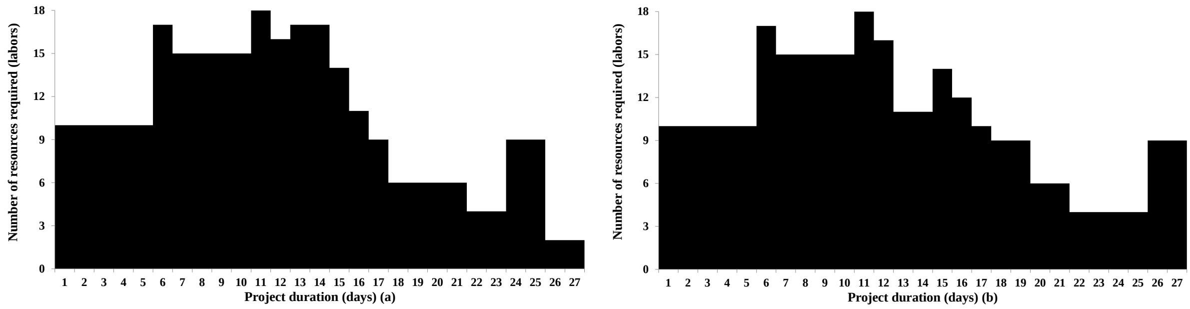

Figure 2: Resource usage histogram before (a) and after (b) resource leveling process.

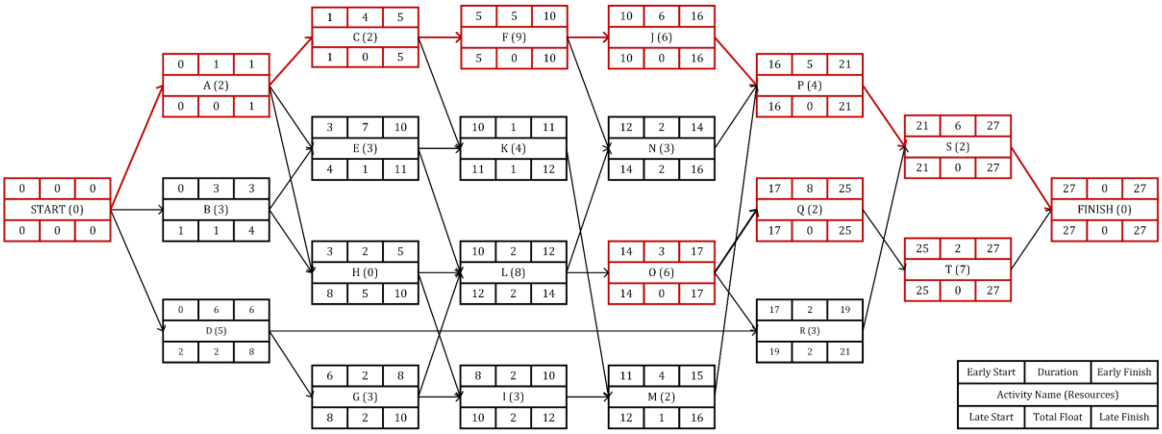

Figure 3: CPM network diagram with 21 days of total float after resource leveling.

Table 1. Frequencies of the sum of the total floats of the 348 schedules with $z_{min} = 90\ labor/day$.

Sum of total floats of schedules	Number of schedules
21	1
20	4
19	10
18	19
17	30
16	41
15	48
14	50
13	46
12	38
11	28
10	18
9	10
8	4
7	1

In summary, the optimal schedule is generated by the proposed model with a resource leveling objective function of 90 labor/day and a sum of the total floats of 21 days. Following the process of resource leveling, it was determined that the result of the objective function for the project decreased from 112 labor/day to 90 labor/day, indicating a 20% improvement. Consequently, the proposed model enhances overall project performance by providing users with a smooth resource utilization histogram and maximum schedule flexibility.

Conclusion

A major obstacle in resource management is dealing with fluctuations in resource usage, which can lead to decreased labor efficiency, longer project durations, and higher project costs. When it comes to managing resources, one of the two most common approaches is resource leveling.

Resource leveling aims to maintain a constant project duration and resource requirements while minimizing fluctuations in resource utilization. In the relevant literature, a leveled resource use histogram can be achieved by using an objective function, such as "minimization of the sum of the absolute deviations between resource usage for a given time interval (day, week, etc.) and the average resource usage". The objective function used to level resources can be different, but different schedules may achieve the same optimal result. One of the most difficult tasks for schedulers is to determine the best schedule out of several options which achieve the same result for the objective function utilized to level resources. Even though numerous studies have been conducted on resource leveling, none have specifically focused on identifying the most optimal schedule among multiple schedules which achieve the same optimum result for the objective function employed in resource leveling. The present study aimed to address the lack of such research.

This study aimed to develop a decision support model to determine the most suitable schedule following resource leveling in construction projects. When multiple schedules achieve the same optimum result for the objective function, the proposed model provides to the user the schedule that maximizes the sum of the total floats of activities. The fundamental rationale behind this approach is to pick the schedule that offers the greatest level of flexibility among the schedules that have the most evenly distributed resource utilization histogram. Put simply, the proposed decision-support model enables users to maximize schedule flexibility while leveling resources. To demonstrate the practical application of the proposed model in a construction project, a case study was conducted. A CPM network diagram consisting of 20 activities is used as an example. The implementation of the proposed model on the example revealed a 20% improvement in the objective function result for the project, which decreased from 112 labor/day to 90 labor/day. After investigating the results, the proposed model concluded that 348 out of 24,971 schedules achieved the optimal objective function result. However, out of the 348 schedules, there is only one schedule that offers the highest level of flexibility (i.e., 21 days of total float). With maximum schedule flexibility and a smooth resource utilization histogram, the proposed model consequently improves the overall performance of the project. Professionals in the construction industry can effectively manage resources, adjust to changes, minimize risks, and accomplish projects on time with a flexible, and resource-balanced schedule.

References

Chen, P. H., & Weng, H. (2009). A two-phase GA model for resource-constrained project scheduling. *Automation in Construction, 18*(4), 485-498.

Chilton, M. A. (2022). Resource allocation in it projects: using schedule optimization. *International Journal of Information Systems and Project Management*, 2(3), 47-59.

Damci, A., & Polat, G. (2014). Impacts of different objective functions on resource leveling in construction projects: a case study. *Journal of Civil Engineering and Management*, *20*(4), 537-547.

Damci, A., Polat, G., Akin, F. D., & Turkoglu, H. (2019). Resource levelling with float consumption rate. *In Creative Construction Conference 2019* (pp. 597-602). Budapest University of Technology and Economics.

Easa, S. M. (1989). Resource leveling in construction by optimization. *Journal of Construction Engineering and Management*, *115*(2), 302-316.

Erdal, M., & Kanit, R. (2021). Scheduling of construction projects under resource-constrained conditions with a specifically developed software using genetic algorithms. *Tehnički Vjesnik*, *28*(4), 1362-1370.

Hariga, M., & El-Sayegh, S. M. (2011). Cost optimization model for the multiresource leveling problem with allowed activity splitting. *Journal of Construction Engineering and Management*, *137*(1), 56-64.

Hegazy, T. (1999). Optimization of resource allocation and leveling using genetic algorithms. *Journal of Construction Engineering and Management*, *125*(3), 167-175.

Hossein Hashemi Doulabi, S., Seifi, A., & Shariat, S. Y. (2011). Efficient hybrid genetic algorithm for resource leveling via activity splitting. *Journal of Construction Engineering and Management*, *137*(2), 137-146.

Leu, S. S., Yang, C. H., & Huang, J. C. (2000). Resource leveling in construction by genetic algorithm-based optimization and its decision support system application. *Automation in Construction*, *10*(1), 27-41.

Lu, M., Lam, H. C., & Dai, F. (2008). Resource-constrained critical path analysis based on discrete event simulation and particle swarm optimization. *Automation in Construction*, *17*(6), 670-681.

Mattila, K. G., & Abraham, D. M. (1998). Resource leveling of linear schedules using integer linear programming. *Journal of Construction Engineering and Management*, *124*(3), 232-244.

Popescu, C., & Borcherding, J. D. (1975). *How to use CPM in practice*. Department of Civil Engineering, University of Texas at Austin.

Senouci, A. B., & Adeli, H. (2001). Resource scheduling using neural dynamics model of Adeli and Park. *Journal of Construction Engineering and Management*, *127*(1), 28-34.

Son, J., & Skibniewski, M. J. (1999). Multiheuristic approach for resource leveling problem in construction engineering: Hybrid approach. *Journal of Construction Engineering and Management*, *125*(1), 23-31.

Su, Z., Qi, J., & Wei, H. Y. (2015). A float-path theory and its application to the time-cost tradeoff problem. *Journal of Applied Mathematics*, 2015, 1-17.

Tran, D. H., & Long, L. D. (2018). Project scheduling with time, cost and risk trade-off using adaptive multiple objective differential evolution. *Engineering, Construction and Architectural Management*, 25(5), 623-638.

Pareto Front Optimization of Time and Cost: Application of Multi-Objective Optimization in Multi-Project Management

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Abstract

Construction projects are characterized by their high level of complexity and fragmented nature; hence, require proper planning and monitoring. Having an optimized plan for a construction project is crucial as it brings several benefits such as efficient use of resources, increase in performance and reduction in cost. Therefore, in the construction management field, optimization problems have been extensively studied under different scenarios. The majority of existing studies mainly focus on investigating the project performance by evaluating multiple success criteria of a single project. However, many construction firms are managing multiple projects simultaneously. To capture the real-world situation, it is essential to study the applications of optimization techniques within the context of portfolio management where multiple projects are analyzed. Furthermore, it is possible to gain advantage by scheduling activities with shared resources, such as labor and machinery, among different projects based on the requirements while not violating project success criteria. To respond to these needs, this study aims to explore the benefits of multi-objective optimization in multi-project environment. Toward this, Pareto front optimization of time and cost is examined within the context of portfolio management. A hypothetical case example involving multiple success criteria is used to demonstrate the practical benefits of the proposed approach.

Keywords: *multi-objective optimization, multi-project scheduling, Pareto front, portfolio management, time and cost optimization.*

Introduction

Construction projects necessitate careful planning and supervision due to their high degree of complexity and fragmented nature. For a construction project to be successful, a number of criteria can be evaluated as the characteristics of construction projects demand different objectives to be achieved, which are mainly related to duration, cost, quality, sustainability, and productivity. Among these objectives, time and cost related ones are the prominent concerns in the construction industry. To meet these project success criteria, researchers have been put excessive effort on solving multi-objective optimization problems for many years.

The duration and cost related objectives can be achieved by modelling the project scheduling problem analytically as an optimization problem and solving it to its optimum. However, there is an inevitable trade-off between duration and cost since accelerating activities results in higher direct expenses but also lower indirect costs. This trade-off between time and cost is known as the time-cost trade-off (TCTO) problem in the optimization domain. Though, in practice, the resources related to construction works are present in discrete units, early research on TCTO problem model the relation between time and cost as continuous. Later, the researchers have studied the same problem in a discrete space which captures the real nature of the problem, naming it as discrete time-cost trade-off (DTCTO) problem. In the literature, most commonly studied problems are deadline problem, where the objective is to minimize total cost for a known deadline; budget problem, where the objective is to minimize total duration without exceeding the budget; and Pareto front problem, which involves determination of the non-dominated time-cost profile over the set of feasible project durations (Vanhoucke & Debels, 2007), also called the Pareto front, or the efficient frontier.

Apart from the necessity to consider duration and cost related objectives simultaneously, which addresses multi-objective optimization, the DTCTO problem can be studied in a multi-project environment, which addresses portfolio management. The solution of the Pareto front problem is a set of non-dominated solutions, each of which is not better than the other in terms of solution quality. The decision-maker can choose between these solutions based on certain preferences. Having multiple solutions of equal quality instead of a single optimal solution provides flexibility to the decision-maker; however, the selection is often subjective. When the Pareto front problem is modeled within the context of multi-project environment, the decision-maker can choose the best solution alternative such that an overall optimized solution can be obtained by considering requirements and constraints of multiple projects. The aim of this proceeding is to reveal the potential benefits of solving the Pareto front optimization of discrete time-cost trade-off (DTCTO) problem in multi-project environment.

Literature Review

The Pareto front optimization of discrete time-cost trade-off (DTCTO) problem has been studied over the years by many researchers. Since the Pareto front DTCTO problem is proven to be non-deterministic polynomial-time hard (NP-hard), the researchers have put effort to find solution techniques so as to decrease computational time to obtain solutions of high quality. In terms of the solution method, the existing studies can be categorized into three groups; exact methods, heuristic methods, and meta-heuristic methods. Exact methods guarantee finding the optimal solution, whereas heuristic and meta-heuristic methods do not guarantee, but may end up finding the optimal solution. Furthermore, there are many variants of the Pareto front DTCTO problem where different aspects are included to capture the real-life occurrences such has uncertainty.

In an earlier work, De et al. (1995) introduced a centralized dynamic programming model with parallel modules, through implementing modular decomposition and incremental reduction. In another study, Demeulemeester et al. (1996) presented two dynamic programming methods; one of which uses node reduction to convert the schedule network into a series/parallel network, and the other method reduces the number of possible alternatives for time-cost combinations. Demeulemeester et al. (1998) embedded horizon-varying approach into branch-and-bound algorithm as an exact solution method, applying branching to time-cost alternatives based on the quality of the underestimation of piecewise linear time-cost curves. Another study that aims to obtain the optimal solution includes a mixed-integer programming model where delay penalty, incentive payment, and lag/lead times between activity relations are included (Chassiakos, 2005).

Evolutionary algoritms can produce multiple optimal solutions in a single iteration due to their population-based nature; hence, they are suitable for solving multi-objective optimization problems. Genetic algorithms (GAs) are often implemented for the optimization problems due to their capability of achieving high quality solutions. Feng et al. (1997) developed GA to solve the Pareto front DTCTO problem, assuming that the relationship between time and cost is linear. In a later work, Zheng et al. (2005) proposed a GA with the implementation of Pareto ranking as a selection criterion and niche formation to improve population diversity, and applied modified adaptive weight approach to prioritize objectives depending on the quality of the previous generation. Among the meta-heuristic methods, particle swarm optimization (PSO) is one of the most powerful algorithms. Yang (2007) presented a modified PSO where the non-dominated solutions are stored and updated in a separate achieve to increase diversity of solutions and speed up converge capability. Zhang and Li (2010) implemented sparse-degree and roulette-wheel selection into PSO algorithm. Ant colony optimization (ACO) is another meta-heuristic method that produces promising results. Ng and Zhang (2008) developed an ACO algorithm by implementing modified adaptive weight approach for the evaluation of fitness values, Afshar et al. (2009) developed a multi-colony non-dominated achiving ACO algorithm where separate ant colonies are assigned to objectives of time and cost minimization. Zhang and Ng (2012) proposed a decision support system that employs ACO with modified adaptive weight approach.

Some researchers aim to benefit from strengths of a heuristic and a meta-heuristic method. For instance, Aminbakhsh and Sonmez (2017) introduced a hybrid optimization method that combines modified Siemens approximation heuristic and particle swarm optimization method for the Pareto front problem where the solution space is discrete. Another study includes an integrated multi-objective optimization by combining genetic algorithm and a heuristic considering trade-offs between time-cost, cost-quality, sustainability-cost, and productivity-safety (Koo et al., 2015).

Besides deterministic consideration of duration and cost values of activities, there exists a stochastic problem definition for the time-cost trade-offs, where uncertainties are involved. Eshtehardian et al. (2008) applied fuzzy set theory to solve stochastic Pareto front problem where the uncertainties in time and cost of the activities are considered. Later, Eshtehardian et al. (2009) evaluated the implementation of fuzzy set theory into genetic algorithm considering the risk acceptance level and degree of optimism of the decision maker. Kalhor et al. (2011) employed an ant colony optimization method for the fuzzy Pareto front problem where different performance metrics are used to evaluate the performance of the algorithm.

Although the Pareto front DTCTO problem has been examined by many researchers over the years, there is a lack of research that investigates the Pareto front DTCTO problem in multi-project environment. One of the existing studies includes developing an elitist non-dominated sorting genetic algorithm for the multi-project Pareto front problem, optimizing the objective functions related to financing cost, profit, and resource allocation (El-Abbasy et al., 2016). In multi-objective optimization problems, a set of non-dominated optimal solutions is produced where no solution is better than the other with respect to conflicting objectives. After obtaining the complete Pareto front, it is decision-maker's choice to come up with a single solution among several equally favorable solutions along the Pareto front. To decide on the "best" solution, planners and/or managers have to use their judgement, which is generally subjective. Existing studies rely on the subjective preference of the decision-maker for the selection of final solution from the set of non-dominated solution. However, the decision-maker can consider the requirements and constraints related to other projects in a company's portfolio in order to make the selection in a more grounded way. This proceeding investigates the potential benefits of examining the Pareto front solutions in practice considering requirements of multiple projects simultaneously.

Multi-Objective Optimization

Independent of the problem domain, optimization refers to finding one or more feasible solutions which corresponds to extremes of one or more objectives. In case of multiple objectives, no solution can be regarded as an optimal solution, instead, a number of optimal solutions forms a set. Furthermore, a gain in one objective cannot be obtained without a loss in the other objective, which leads to a trade-off between them. Hence, no solution in the set of optimal solutions is better than any other in the same set.

Despite there exist many optimal solutions, from the practical point of view, a decision-maker needs to choose a single one. Deb (2001) suggests two approaches to obtain the solution for a multi-objective optimization problem; namely "ideal procedure" and "preference-based". In the ideal procedure, it is suggested that one can compare the solution alternatives according to advantages and disadvantages after taking into account a higher-level parameter, often being a qualitative consideration. First step of this approach is to find the set of optimal solutions; afterwards, the decision-maker can choose one of these solutions using the higher-level information. In the preference-based approach, one can assign relative weights to different objectives depending on the preference, creating a single objective function. This method is highly subjective and the solutions obtained are sensitive to the preference factors set by the decision-maker.

The mathematical formulation of the general discrete time-cost trade-off (DTCTO) problem which is the modified version of the original formulation (De et al., 1995) that contains indirect cost is as follows (Aminbakhsh and Sonmez, 2017):

$$\text{minimize} \sum_{j=1}^{S} \sum_{k=1}^{m_j} dc_{jk} x_{jk} + D \times ic \tag{1}$$

subject to

$$\sum_{k=1}^{m_j} x_{jk} = 1, \qquad \forall j = \{1,2,\dots,S\} \tag{2}$$

$$\sum_{k=1}^{m_j} dc_{jk} x_{jk} + St_j \leq St_l, \qquad \forall l \in Sc_j \qquad and \qquad \forall j = \{1,2,\dots,S\} \tag{3}$$

$$D \geq St_{S+1} \quad (4)$$

$$St_0 = 0 \quad (5)$$

where dc_{jk} = direct cost of mode k for activity j; x_{jk} = binary decision variable that corresponds to determination of which mode alternative k is selected for activity j; ic = indirect cost per day; D = project duration; d_{jk} = duration of mode k for activity j; St_j = start time for activity j; and Sc_j = the set of immediate successors for activity j.

The objective function is to minimize the sum of direct cost and indirect cost. The optimum cost C_a for a particular project deadline D_a can be obtained by setting a constraint to the project duration D as follows:

$$D = D_a \quad (6)$$

First introduced by the Italian economist Vilfredo Pareto, "pareto optimality" refers to the situation in which there are several criteria and no amount of resources may be reallocated to improve one criterion at the cost of one or more other criteria (Mandal, J. K. et al, 2018). The series consisting of optimal solutions for a multi-objective problem with conflicting objectives is known as the "Pareto front", also called the efficient frontier. The Pareto front problem involves determination of the complete and non-dominated optimal duration-cost solutions over the set of feasible project durations. The following criteria are used to define Pareto-dominance optimality:

- A decision vector u is said to weakly dominate another solution v if and only if $D_u \leq D_v$ and $C_u \leq C_v$ which is denoted as $u \succcurlyeq v$.

$$u \succcurlyeq v \quad iff \quad \forall y: \; f_y(u) \leq f_y(v) \quad (7)$$

- A solution v is considered to be dominated if and only if there is already another solution u in the efficient frontier such that $D_u \leq D_v$ while $C_u \leq C_v$, and one of these inequalities holds strictly, which is denoted as $u \succ v$.

$$u \succ v \quad iff \quad \forall y: \; f_y(u) \leq f_y(v) \quad and \quad \exists y: \; f_y(u) < f_y(v) \quad (8)$$

- A decision vector u is said to strongly dominate solution v if and only if $D_u < D_v$, and $C_u < C_v$, which is denoted as $u \succ v$.

$$u \succ\succ v \quad iff \quad \forall y: \; f_y(u) < f_y(v) \quad (9)$$

where f_y represents the y^{th} objective function value. Solution u is said to be *Pareto optimal* as $\forall u, v \in O \; if \; \nexists v: u \succ u$; union of all of which forms the Pareto front denoted by O.

In the case of two objectives that are sought to be minimized, as in the DTCTO problem, the solution of the Pareto front problem yields the following graphical representation (Figure 1).

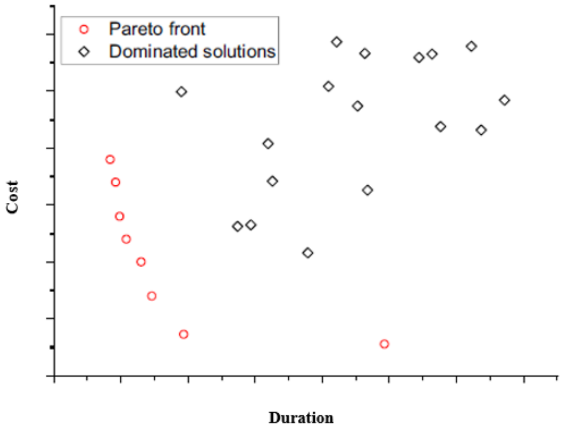

Figure 1: Graphical representation of Pareto front (adapted from Guo and Zhang, 2022).

Practical Benefits of Pareto Front

The solution of multi-objective optimization gives the Pareto front that consists of non-dominated solutions with equal quality in terms of desired objectives. Out of a number of Pareto optimal solutions, the decision-maker has to choose a single solution that forms the project plan. Having several optimal solutions in lieu of a single solution provides flexibility for the decision-maker. Yet, the selection of solution alternatives depends on the subjective judgment of the decision-maker. Evaluating the Pareto front solutions by taking into account requirements and constraints of multiple projects at hand leads to some practical benefits, and impartial selection of solution alternatives. These benefits include but not limited to the following:

- Efficient resource allocation between different projects.
- Cost reduction due to efficient mobilization of resources between different projects.
- Decrease in idle times of resources.
- Adaptation to changing project demands.

To illustrate the potential benefits of solving the Pareto front problem in multi-project environment, a hypothetical case example that consists of two projects is presented (Table 1). Consider a construction firm that has two similar projects in its portfolio to be executed, almost in series, i.e., the start time of the second project is near the finish time of the first project. In addition, they share the same workforce and equipment to perform the works.

Table 1. Hypothetical Pareto fronts.

Pareto front for Project 1		Pareto front for Project 2	
Duration (days)	*Cost ($)*	*Duration (days)*	*Cost ($)*
152	838,000	146	764,000
159	827,000	151	759,000
165	824,000	154	752,000
172	812,000	163	743,000
177	809,000	175	737,000
183	804,000		

When aforementioned benefits are considered, the project planner or the manager can choose the time-cost alternative based on the start time of the second project. For example, if there are 175 days between the start time of the projects, it will be reasonable to choose the solution with the duration of 172 days with the corresponding cost $812,000, even this alternative is not the one with the least duration or the least cost. If, on the other hand, one of the solution alternatives with the duration less than 172 days is selected, the resources would remain idle until mobilization to the second project, which is unfavorable.

Conclusions

An optimized plan is essential for construction projects as it helps project managers or any other project participant to improve performance. The complexity and unpredictability of construction projects necessitate the simultaneous consideration of multiple objectives to achieve project success. The solution of multi-objective optimization problem yields a Pareto front curve that includes multiple optimal solutions. Often, the selection of one solution from the Pareto front curve is dependent on the subjective judgment of the decision-maker. In this proceeding, it is proposed that the decision-maker can choose the best solution according to the requirements of other projects in the company portfolio. Furthermore, the benefits of having the Pareto front solution from a practical standpoint are discussed using a hypothetical case example, which results in overall optimized project plans.

References

Afshar, A., Ziaraty, A. K., Kaveh, A., & Sharifi, F. (2009). Nondominated archiving multicolony ant algorithm in time–cost trade-off optimization. *Journal of Construction Engineering and Management*, *135*(7), 668-674.

Aminbakhsh, S., & Sonmez, R. (2017). Pareto front particle swarm optimizer for discrete time-cost trade-off problem. *Journal of Computing in Civil Engineering*, *31*(1), 04016040.

Chassiakos, A. P., & Sakellaropoulos, S. P. (2005). Time-cost optimization of construction projects with generalized activity constraints. *Journal of Construction Engineering and Management*, *131*(10), 1115-1124.

De, P., Dunne, E. J., Ghosh, J. B., & Wells, C. E. (1995). The discrete time-cost tradeoff problem revisited. *European Journal of Operational research*, *81*(2), 225-238.

Deb, K. (2001). *Multi-objective optimization using evolutionary algorithms* (Vol. 16). John Wiley & Sons.

Demeulemeester, E. L., Herroelen, W. S., & Elmaghraby, S. E. (1996). Optimal procedures for the discrete time/cost trade-off problem in project networks. *European Journal of Operational Research*, *88*(1), 50-68.

Demeulemeester, E., De Reyck, B., Foubert, B., Herroelen, W., & Vanhoucke, M. (1998). New computational results on the discrete time/cost trade-off problem in project networks. *Journal of the Operational Research Society*, *49*(11), 1153-1163.

El-Abbasy, M. S., Elazouni, A., & Zayed, T. (2016). MOSCOPEA: Multi-objective construction scheduling optimization using elitist non-dominated sorting genetic algorithm. *Automation in Construction*, *71*, 153-170.

Eshtehardian, E., Afshar, A., & Abbasnia, R. (2008). Time–cost optimization: using GA and fuzzy sets theory for uncertainties in cost. *Construction Management and Economics*, *26*(7), 679-691.

Eshtehardian, E., Afshar, A., & Abbasnia, R. (2009). Fuzzy-based MOGA approach to stochastic time–cost trade-off problem. *Automation in Construction*, *18*(5), 692-701.

Feng, C. W., Liu, L., & Burns, S. A. (1997). Using genetic algorithms to solve construction time-cost trade-off problems. *Journal of Computing in Civil Engineering*, *11*(3), 184-189.

Guo, K., & Zhang, L. (2022). Multi-objective optimization for improved project management: Current status and future directions. *Automation in Construction*, *139*, 104256.

Kalhor, E., Khanzadi, M., Eshtehardian, E., & Afshar, A. (2011). Stochastic time–cost optimization using non-dominated archiving ant colony approach. *Automation in Construction*, *20*(8), 1193-1203.

Koo, C., Hong, T., & Kim, S. (2015). An integrated multi-objective optimization model for solving the construction time-cost trade-off problem. *Journal of Civil Engineering and Management*, *21*(3), 323-333.

Mandal, J. K., Mukhopadhyay, S., & Dutta, P. (2018). *Multi–Objective Optimization.* Springer, Singapore.

Ng, S. T., & Zhang, Y. (2008). Optimizing construction time and cost using ant colony optimization approach. *Journal of Construction Engineering and Management*, *134*(9), 721-728.

Vanhoucke, M., & Debels, D. (2007). The discrete time/cost trade-off problem: extensions and heuristic procedures. *Journal of Scheduling*, *10*, 311-326.

Yang, I. T. (2007). Using elitist particle swarm optimization to facilitate bicriterion time-cost trade-off analysis. *Journal of Construction Engineering and Management*, *133*(7), 498-505.

Zhang, H., & Li, H. (2010). Multi-objective particle swarm optimization for construction time-cost tradeoff problems. *Construction Management and Economics*, *28*(1), 75-88.

Zhang, Y., & Thomas Ng, S. (2012). An ant colony system based decision support system for construction time-cost optimization. *Journal of Civil Engineering and Management*, *18*(4), 580-589.

Zheng, D. X., Ng, S. T., & Kumaraswamy, M. M. (2005). Applying Pareto ranking and niche formation to genetic algorithm-based multiobjective time–cost optimization. *Journal of Construction Engineering and Management*, *131*(1), 81-91.

Optimizing Holt-Winters Exponential Smoothing Parameters for Construction Cost Index Forecasting: An Update

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Abstract

The aim of this paper is to compare the forecast results from our previous study with actual data and evaluate the accuracy of Holt-Winters forecasting for the Construction Cost Index (CCI). Our Previous research aims to enhance the accuracy of CCI forecasting using Holt-Winters exponential smoothing (ES) by optimizing its parameters, focusing on minimizing the Mean Absolute Percentage Error (MAPE) for precise CCI forecasts. To reach this aim, The Holt-Winters model parameters are optimized through Particle Swarm Optimization (PSO) and Walk-Forward Cross-Validation (WFCV). PSO, a metaheuristic optimization algorithm, is being applied to search for optimal values of the smoothing parameters (alpha, beta, and gamma) that determine the weightage of past observations, trends, and seasonality, respectively. WFCV assesses the model's performance and ensures robustness. Reduced MAPEs of 22 for CCI forecasts and 2 for training data are the findings of the optimized Holt-Winters model. The obtained alpha, beta, and gamma values are 0.99, 0.77, and 0, respectively, highlighting the importance of while neglecting seasonality. Convergence graphs demonstrate the superiority of the optimization approach over conventional parameter values or random selections. By employing PSO and WFCV, the study efficiently fine-tunes the Holt-Winters model for precise CCI forecasting. Optimized parameter values enable data driven decision-making in construction project cost estimation and budget management. The increased volatility could impact the forecasting model's performance, potentially diminishing its accuracy. Further investigation into forecasting highly volatile time series is essential to effectively tackle these challenges. .Continuously forecasting to detect divergences is a critical aspect underscored in this study, as is interpreting forecast results with probability intervals.

Keywords: *construction cost index, forward cross-validation, holt-winters, metaheuristics, parameter optimization,. particle swarm optimization.*

Introduction

The aim of this paper is to compare the forecast results from our previous study with actual data and evaluate the accuracy of Holt-Winters forecasting for the CCI. Our previous research aimed to enhance the accuracy of CCI forecasting using Holt-Winters exponential smoothing by optimizing its parameters, focusing on minimizing the Mean Absolute Percentage Error (MAPE) for precise forecasts (Tüz & Ebesek, 2023).

A brief introduction summarizing our previous study follows: The CCI is crucial for project cost estimation, inflation adjustments, and budgeting, guiding resource allocation, project planning, and financial reporting while monitoring cost changes influenced by economic factors to manage risks effectively (Liu et al., 2021). Within the construction sector, the CCI serves as a significant metric, assessing cost trends and facilitating estimation and budgeting endeavours (Velumani & Nampoothiri, 2021). Accurate CCI forecasts enable precise bids, avoiding under or overestimations (Ashuri & Lu, 2010).

However, the reliability and validity of the CCI pose significant implementation challenges, potentially impacting cost predictions (Choi et al., 2021). The CCI may not fully reflect local variations or comprehensively consider macroeconomic influences, necessitating adjustments and the exploration of other economic indicators (Zhan et al., 2021; Fachrurrazi, 2016).

Previous research aims to improve CCI estimate accuracy by integrating PSO with the Holt-Winters ES model and WFCV, focusing on minimizing MAPE. Accurate CCI forecasts enhance decision-making, resource allocation, and risk management, benefiting construction project planning and execution.

The CCI's multifaceted role includes project cost estimation, inflation adjustment, budgeting, resource allocation, project planning, financial reporting, and risk management (Tey et al., 2015; Ashuri & Shahandashti, 2012; Liu et al., 2021). It captures price shifts over time, aiding budget formulation, cost modeling, and projection (Tey et al., 2015). The CCI is pivotal in forecasting future movements, budget planning, contract bidding, and assessing unit price offers in competitive bidding (Choi et al., 2021; Fachrurrazi, 2016).

Various forecasting models, including linear models, ES methodologies, multivariate time series models, and smoothing techniques, predict the CCI, drawing insights from historical data (Choi et al., 2021; Velumani & Nampoothiri, 2021). SARIMA excels in in-sample CCI forecasting, while the Holt-Winters ES model performs well in out-of-sample scenarios (Ashuri & Lu, 2010).

Wang and Ashuri's (2017) study on ENR CCI using the Holt-Winters method highlights its superior forecast accuracy. Similarly, Aydınlı (2022) focuses on Turkey's CCI, also finding the Holt-Winters method effective. (Choi et al., 2021) note the enhanced performance of their ES models compared to expert forecasts. Ashuri and Lu (2010) and Joukar and Nahmens (2016) underscore the predictability of Holt ES models, enhancing cost estimations and budget planning.

Velumani and Nampoothiri (2021) emphasize the predictability of their ES models for the Construction Industry Development Council CCI. Shahandashti and Ashuri (2013) also highlight the effectiveness of Holt ES models. Jiang et al. (2022) demonstrate the exceptional predictive capabilities of the Holt model.

PSO is recognized for its adaptability and broad applicability (Marini & Walczak, 2015). Cross-validation, a widely used resampling method, assesses a predictive model's generalization ability and prevents overfitting, ensuring accurate model selection and parameter tuning (Berrar, 2019).

Updating with actual values is essential to validate and refine forecasting models, ensuring their accuracy and reliability in capturing real-world dynamics. This process allows for the assessment of model performance, identification of discrepancies, and adjustment of parameters to improve future predictions. By incorporating actual data, we can enhance the model's robustness and applicability, thereby providing more precise and dependable forecasts.

Methodology

At the onset of the methodology section, a succinct introduction serves to recall our previous research endeavours: Our Previous research adopts an empirical approach to enhance the accuracy of CCI forecasting using the Holt-Winters ES method. The study utilizes a combination of quantitative data analysis and optimization techniques to achieve the research objectives.

The data used in the study originates from the Turkish Statistical Institute, specifically the dataset relating to the CCI. This dataset monitors alterations in construction costs, encompassing both labor and materials, providing valuable insights for forecasting. Data is collected monthly across Turkey.

Data analysis and optimization are carried out using the Anaconda platform, with Python and JupyterLab facilitating research code development and execution. The Holt-Winters model incorporating additive trend and seasonal components is used for forecasting the CCI. By setting the gamma parameter to 0, the focus is on trend and level components, enhancing model interpretability and stability, and minimizing the complexity of handling noisy data.

Additionally, MAPE measures the average percentage deviation between forecasted and actual values, suitable for comparing accuracy across diverse datasets. MAPE values can be interpreted as follows: 0 signifies a perfect forecast, 10 reflects excellent accuracy, 20 indicates good accuracy, 30 implies fair accuracy, 40 denotes moderate accuracy, and 50 suggests poor accuracy.

To optimize the Holt-Winters model's smoothing parameters (alpha, beta, gamma), the PSO algorithm is employed. This algorithm minimizes the MAPE by exploring the parameter space with swarms of particles. The objective function uses the product of mape_predicted and mape_forecasted, encouraging balanced outcomes for both metrics. The square root operation moderates the product's influence, aiding interpretation.

The optimized Holt-Winters model's performance is evaluated using WFCV, which simulates real-world forecasting scenarios by using the last 12 periods of the training dataset as the test dataset. This evaluation ensures model reliability and robustness.

For PSO optimization, parameters are set as swarmsize=15 and maxiter=30, with bounds defined as [0.001, 0.001, 0] to [1, 1, 0] for alpha, beta, and gamma. The minimize function finds the optimal smoothing parameters, enhancing forecasting accuracy.

The methodology section describes the comprehensive approach to optimizing the Holt-Winters model, including PSO and WFCV, aiming to provide reliable CCI estimates.

The methodology employed in our current paper involves visually presenting both actual and forecasted values on a graph. This approach enables a direct comparison with the results obtained in our previous research, facilitating an evaluation of the accuracy and reliability of the forecasting model.

Results

A brief introduction summarizing Results section of our previous study follows: The Seasonal Trend Decomposition of the CCI is presented, breaking down CCI into trend, seasonality, and residuals, which aids in understanding underlying patterns and forecasting. The one-period change in CCI values over time is depicted, illustrating the magnitude and direction of fluctuations, thereby facilitating the analysis of short-term trends and volatility. The distribution of CCI values is visualized through a histogram, providing insights into the frequency, central tendency, and variability in construction costs.

The convergence of the PSO objective function during optimization is demonstrated, highlighting PSO's efficiency in minimizing the product of prediction and forecast accuracy with special target function. This leads to optimal values of alpha, beta, and gamma for the Holt-Winters model, assessing optimization efficiency and convergence stability. The MAPE predicted by the PSO algorithm during parameter optimization is shown, reflecting continuous improvement in prediction accuracy. Additionally, the convergence of MAPE forecasted by the PSO algorithm is depicted, indicating a reduction in forecast errors and ongoing enhancement in forecast accuracy, thus validating the PSO's effectiveness in refining the model's predictions.

Below is a concise recapitulation of the results obtained in our previous study: The optimized model showed significantly reduced MAPE values of 22 for the CCI predictions and an impressively low MAPE value of 2 for the training data. Parameter values alpha=0.99, beta=0.77 and gamma=0 emphasized the importance of past observations and trends, ignoring seasonality. All detailed methodologies, algorithms, and calculations can be found in the previous study.

Figure 1 presents the outcomes of the Holt-Winters model optimization for the CCI. This graph compares actual, fitted, and forecasted CCI values. It serves as a valuable tool for evaluating model performance and visualizing the accuracy of optimized forecasts.

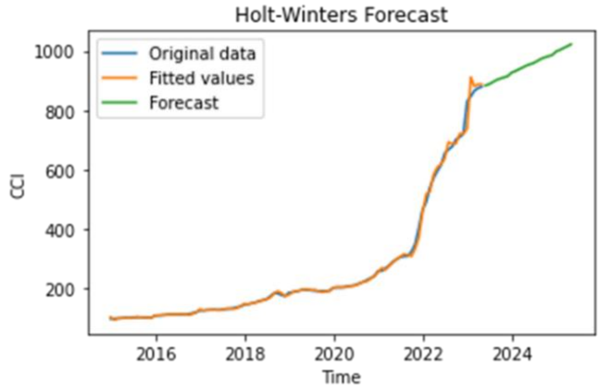

Figure 1: Holt-Winters CCI forecast.

Figure 2 illustrates the alignment of this study's forecast values with the dataset used by the baseline study. The blue line represents the CCI values from the test dataset, the yellow line showcases the fitted values obtained after the prediction process, and the green line depicts the values obtained following the forecasting process.

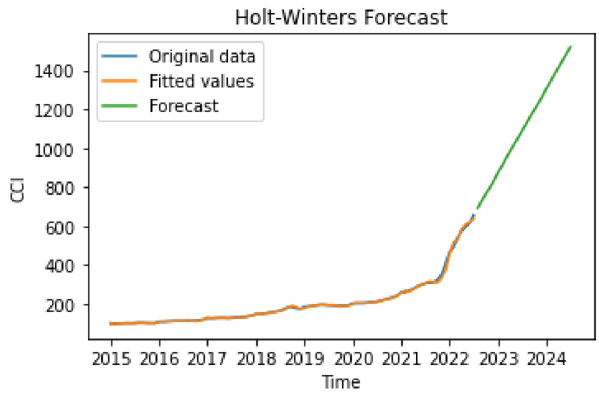

Figure 2: Forecast result of presented model applied to baseline study data in previous study.

Figure 3 provides a detailed comparison of forecasted and actual) values. It presents the actual CCI alongside forecast values from both the baseline and previous study periods. Specifically, the baseline study includes 90 data points spanning from January 2015 to June 2022, while the previous study comprises 101 samples from January 2015 to May 2023. The actual CCI time series extends this dataset with 111 samples, covering the period from January 2015 to March 2024. This comprehensive dataset allows for a robust comparison of forecasted versus actual values, enabling a thorough assessment of the model's predictive performance over time and providing insights into its accuracy and reliability.

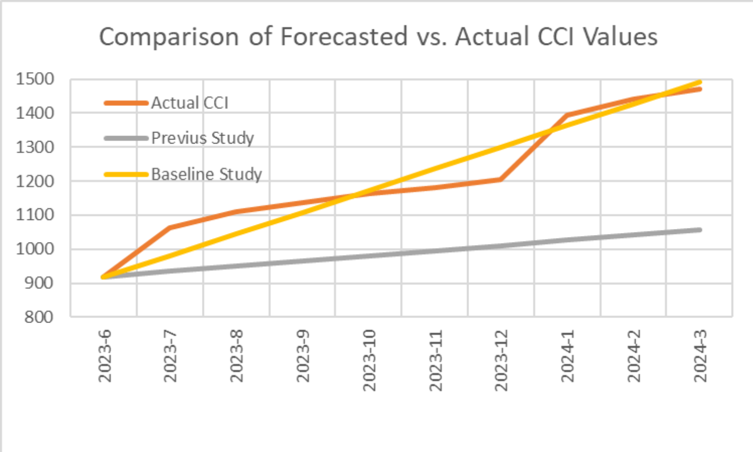

Figure 3: Comparison of forecasted vs. actual CCI.

The last quarter of the time series exhibits significantly higher volatility compared to the initial three-quarters. This heightened volatility appears to be influencing the weakening performance of the forecasting model.

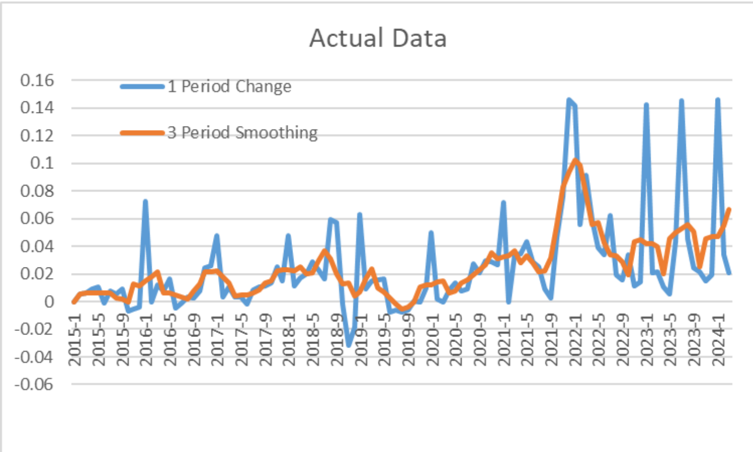

Figure 4: Periodical change of actual CCI.

Figure 4 illustrates the pronounced increase in volatility observed in the last quarter of the time series, contrasting with the relative stability observed in the initial three-quarters. This heightened volatility is indicative of fluctuations that may impact the forecasting model's performance, potentially leading to its declining accuracy. Further research on forecasting highly volatile time series is warranted to better understand and address these challenges.

Conclusion

The previous study focused on optimizing the Holt-Winters ES model parameters for CCI forecasting using PSO and WFCV. The research achieved significantly reduced MAPE values, specifically 22 for CCI forecasts and 2 for training data, underscoring the importance of disregarding seasonality in refining CCI forecasts. The use of WFCV added rigor, ensuring the model's reliability. This innovative optimization approach effectively enhanced CCI forecasting accuracy by minimizing MAPE through parameter optimization of the Holt-Winters ES model.

The success of the optimization methodology demonstrates the potential of metaheuristic techniques such as PSO to improve time series prediction accuracy.

However, the previous study's focus on Turkey may limit the generalizability of findings. Future research should integrate exogenous factors. Increased volatility in the last part of the time series may affect the forecasting model's performance, necessitating further research on forecasting highly volatile time series. Continuously forecasting to detect divergences is a critical aspect underscored in this study, as is interpreting forecast results with probability intervals. Practical recommendations include using shorter forecast horizons in high-volatility environments and adopting a proactive approach with regular updates and robust risk management in volatile or upward-trending scenarios.

Forecasting aims to exploit future information without clinging to certainty. The optimized Holt-Winters ES model can be a crucial tool for construction stakeholders in cost estimation, budgeting, and risk management through data-driven decision-making. Despite inherent uncertainties, data-driven forecasting empowers decision-makers to manage construction costs effectively, providing a reliable measure compared to intuition or rumour. Accurate and informed forecasting approaches are crucial for navigating the complexities and uncertainties in construction cost management.

References

Ashuri, B., & Lu, J. (2010). Time Series Analysis of ENR Construction Cost Index. *Journal of Construction Engineering and Management*, 136, 1227-1237.

Ashuri, B., & Shahandashti, S. M. (2012, April). Quantifying the relationship between construction cost index (CCI) and macroeconomic factors in the United States. *In Vol. 14 of Proc., 48th ASC Annual Int. Conf.* Birmingham, UK: Birmingham City Univ.

Aydınlı, S. (2022). Time series analysis of building construction cost index in Türkiye. *Journal of Construction Engineering, Management & Innovation* (Online), 5(4).

Berrar, D. (2019). Cross-Validation. *Encyclopedia of Bioinformatics and Computational Biology*, 1(April), 542-545.

Choi, C., Ryu, K.R., & Shahandashti, M. (2021). Predicting City-Level Construction Cost Index Using Linear Forecasting Models. *Journal of Construction Engineering and Management*, 147, 04020158.

Fachrurrazi (2016). Study of Unit Price for Competitive Bidding Based on CCI (Construction Cost Index) for Building. *International Journal of Engineering Research and Technology*, 5.

Jiang, F., Awaitey, J., & Xie, H. (2022). Analysis of construction cost and investment planning using time series data. *Sustainability*, 14(3), 1703.

Joukar, A., & Nahmens, I. (2016). Volatility Forecast of Construction Cost Index Using General Autoregressive Conditional Heteroskedastic Method. *Journal of Construction Engineering and Management*, 142, 04015051.

Liu, H., Kwigizile, V., & Huang, W. C. (2021). Holistic framework for highway construction cost index development based on inconsistent pay items. *Journal of Construction Engineering and Management*, 147(7), 04021052.

Marini, F., & Walczak, B. (2015). Particle swarm optimization. A tutorial. *Chemometrics and Intelligent Laboratory Systems*, 149, 153-165.

Shahandashti, S. M., & Ashuri, B. (2013). Forecasting engineering news-record construction cost index using multivariate time series models. *Journal of Construction Engineering and Management*, 139(9), 1237-1243.

Tey, K.H., Lim, S.Y., Yusof, A.M., & Chai, C.S. (2015). T*he implementation of construction cost index (CCI) in Malaysia.*

Tüz, Ö., *&* Ebesek, Ş. (2023). Optimizing Holt-Winters Exponential Smoothing Parameters for Construction Cost Index Forecasting with PSO and Walk-Forward Cross-Validation. ‘’*Kent Akademisi’’*, 16 (4), 2422-2439.

Velumani, P., & Nampoothiri, N. V. N. (2021). Volatility forecast of CIDC Construction Cost Index using smoothing techniques and machine learning. *International Review of Applied Sciences and Engineering*, 12(1), 50-56.

Wang, J., & Ashuri, B. (2017). Predicting ENR Construction Cost Index Using Machine-Learning Algorithms. *International Journal of Construction Education and Research*, 13, 47 - 63.

Zhan, T., He, Y., & Xiao, F. (2021). Construction Cost Index Forecasting: A Multi-feature Fusion Approach. *arXiv preprint* arXiv:2108.10155.

Asset Management Practices and Challenges in Airport Projects: A Case Study

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Abstract

Construction projects' operation and maintenance phase constitutes the longest period of their life cycle, with asset management playing a pivotal role during this stage. While the asset management concept is addressed in case studies across various project types in literature, airport projects require specialized asset management due to their unique characteristics. These include the need for specific design, construction, and management approaches for complex structures (e.g., terminal building and apron), high traffic volume, security risks, diverse stakeholders, intricate operational demands, and 24/7 continuous monitoring. This study aims to investigate current asset management approaches and tools in airports and to identify the best practices, main challenges, and lessons learned. Conducted as a case study, data collection involved online interviews with two professionals, observations through participatory research, and examination of systems and tools utilized for asset management in a large-scale *airport. The findings of this study can assist researchers in developing frameworks and practitioners in enhancing asset management processes.*

Keywords: *airport projects, asset management, case study.*

Introduction and Background

The operation and maintenance stage represents the longest period in a building's life cycle (Kong et al., 2022). Obtaining accurate information during this phase poses challenges (Dixit & Venkatraj, 2019) due to the escalating volume of critical information (such as manufacturers data, specifications, operational instructions, procedures, warranty information, etc.) from the design phase to the Operations and Maintenance (O&M) phase (Becerik-Gerber et al., 2011). Additionally, the absence of specific guidelines for numbering style, semantics, syntax, and schemas (Liu & Issa, 2013; Parsanezhad & Dimyadi, 2013; Becerik-Gerber et al., 2011) and utilizing numerous paper documents, including drawings and contracts in this O&M phase (Kelly et al., 2013), contributes to delays in information processing, information loss, and data disintegration and fragmentation throughout the building's life cycle (Liu & Zettersten, 2016).

Asset management in facility management involves tracking assets and performing maintenance, repair, and replacement activities throughout the entire asset life cycle, including planning, purchase, operation, maintenance, and disposal (International Organization for Standardization, 2018). Companies with a strong operational focus, such as airport operators, place great importance on effective asset management to ensure profitability (Velmurugan et al., 2021).

Studies in the field of asset management encompass various project types, including highway transportation (Shah et al., 2017), production buildings (Roda & Macchi, 2018), educational facilities (Abdelhamid et al., 2015), and diverse building types (Al-Kasasbeh et al., 2020), are documented in the literature. However, airports necessitate specialized case studies on asset management due to their unique characteristics compared to other types of facilities. Airports are asset-intensive business systems that require specific design, construction, and management approaches (Koseoglu et al., 2019). Unlike traditional buildings, airports have complex land-side (i.e., terminal buildings) and air-side (i.e., apron) interfaces (Bertolini et al., 2023) with high traffic volume and security risks (Hein, 2014), necessitating flexible asset management approaches which demand accurate information management and planning efficiency. Moreover, airport projects involve a wide range of stakeholders and intricate operational requirements that demand a comprehensive understanding of asset management practices (Pascarella et al., 2022).

This study aims to examine the current asset management approaches and tools used in airports and to identify best practices, the main challenges encountered, and lessons learned. A case study was performed at a large-scale airport, and the data collection was carried out through online interviews, observations through participatory research, an investigation of systems, tools, and documents used for asset management. The collected data were triangulated to integrate the findings of the study.

Methodology

The case study method is used to examine a topic within its environment (Saunders et al., 2012). Airport asset management is a complex topic, including multi-faceted challenges, and in this paper, the case study method is used to capture contextual information, including the underlying processes and mechanisms. By triangulating data through various sources, such as interviews and observations, researchers can gain a deeper understanding of the problem from multiple perspectives (Yin, 2017).

The selected airport case study is operated by an international company specializing in airport operations. The airport is large-scale (182,000 m^2 terminal size), located in Türkiye, with an average of 17 to 18 million annual passengers. The interviewed experts were selected among the employees of the same company that runs the airport. The positions of these experts are Electrical-Electronic Systems Manager and Logistics and Purchasing Manager, with 19 and 13 years of experience, respectively.

The data collection techniques in this study include 1) interviews with two key professionals, 2) observations through participatory research as two of the authors participated in designing the asset management system of the airport, and 3) an investigation of systems, tools, and documents used for asset management. The data collected from multiple sources were triangulated to integrate the study findings.

During the interviews, experts were asked open-ended questions to investigate the asset management approaches from technical perspectives. The interviews were conducted online at various times, with an average duration of one and a half hours per interview. The questions are as follows:

- Which assets are considered critical and monitored closely to prevent any downtime?
- Do you use any digital tools for asset management?
- What databases are you using to register assets, and how does asset registration change in different databases?
- Are you aware of any asset management standards, and are you using them?
- Do you have an asset management procedure? If yes, how is it implemented?

Based on the answers, best practices, challenges, and lessons learned were identified.

Analysis of the Case Study

The domestic and international terminals of the airport are constructed under the Build-Operate-Transfer (BOT) project delivery method. The airport has a 182,000 m^2 terminal and a 108,000 m^2 parking lot. There are eighteen passenger bridges, eighteen passport control counters, and nine baggage handling systems. The airport served about 18 million passengers before the pandemic and served about 12 million passengers in 2022. It was awarded the best European Airport in 2020, in the category of 15-25 million passengers a year, by Airport Council International.

Approximately 1.000 personnel work at the airport and 700 of them work in the security department. Maintenance teams, both internal and external, are crucial for ensuring uninterrupted airport operations. External teams, which are usually available 24/7, offer urgent maintenance support, while internal teams handle periodic maintenance, as well as maintenance to assets when their warranties expire or specialized maintenance as needed. Manufacturers also play a role, providing feedback on asset conditions and offering maintenance for specific products, such as elevators.

Critical Assets in Airports

An asset that can have a major impact on accomplishing the organization's goals is considered a critical asset (ISO 55000, 2014). In the interviews, experts were asked, "Which assets are considered critical and monitored closely to prevent any downtime?" The critical assets identified are listed below. These critical assets are designated as assets essential for the company to generate income and for the airport to operate effectively without any disruption.

The critical assets are as follows:

- Baggage Handling System (BHS),
- Servers,
- Tomograph and Security Control Systems,
- Flight Information Display System (FIDS),
- Common Use Passenger Processing Systems (CUPPS),
- Enhance Performance X-ray (EPX) Baggage Scanning Systems,
- Common Use Terminal Equipment (CUTE), Public Address Systems,
- Fire Alarm System,

- 400 Hz Electrical Systems,
- Electrical Distribution System,
- Uninterruptible Power Supply (UPS),
- Generators

The list provided includes both apron-side and landside critical assets. Thus, it includes critical assets that are crucial for an airport's entire operation, and if any of them fail, it might have a serious impact, ranging from flight delays to cancellations. The critical assets require a stable power supply to operate effectively. Therefore, electrical distribution system, uninterruptible power supply, generators, and 400 Hz electrical systems are included in the list to provide power to these assets.

Digital Tools and Systems Used

The interviewed experts noted that digital tools were being used in asset management at the airport. The technical affairs department keeps track of assets in Maximo, a Computerized Maintenance Management System (CMMS) software application developed to make asset management in businesses more effective. Because of its scalability and strong data processing capabilities, Maximo is a solution for organizations that handle large-scale assets, such as airports. Maximo is used for asset maintenance, including corrective maintenance and preventive maintenance. It manages asset information in a single database, such as location, condition, history, and maintenance needs. The maintenance team can schedule preventative and corrective maintenance tasks, create and manage work orders, allocate jobs to employees, and keep track of inventory.

The finance department uses Oracle Enterprise Resource Planning (ERP) software application to handle asset records and financial data concurrently. Oracle ERP is also used to keep purchasing data and track inventory lists. With this ERP application, all assets and invoices are stored, and spare parts purchased and stored in the warehouse are tracked. In addition, the warehouse department enters the information on used materials and tracks where the materials were used and how much material is left in the warehouse.

The failure to use these tools properly and adequately can have subsequent consequences, leading to a lack of visibility into the performance of assets and the potential unscheduled downtime, increased maintenance costs, and decreased operational efficiency. Without effective monitoring and data collection, airport asset managers may lack the necessary information to identify and address critical issues, potentially leading to reputational damage.

Asset Management Procedure

The experts detailed the workflows of work order procedures used in asset management. The corrective and preventive maintenance are performed utilizing Maximo (Figure 1). Corrective maintenance is unplanned and reactive and is performed to restore the asset to normal condition after unforeseen failure or malfunction has arisen. Preventive maintenance refers to the practice of conducting routine maintenance tasks at scheduled intervals to mitigate the possibility of unforeseen failures down the line (Stenström et al., 2015). In the investigated airport, preventive maintenance is planned regardless of any failure or malfunction observed with the equipment, and it ensures the effective operation and safety of the assets by minimizing the risk of equipment failure. The workflow of corrective and preventive maintenance in Maximo (Figure 1) is equally essential, but changes in how the work order is triggered.

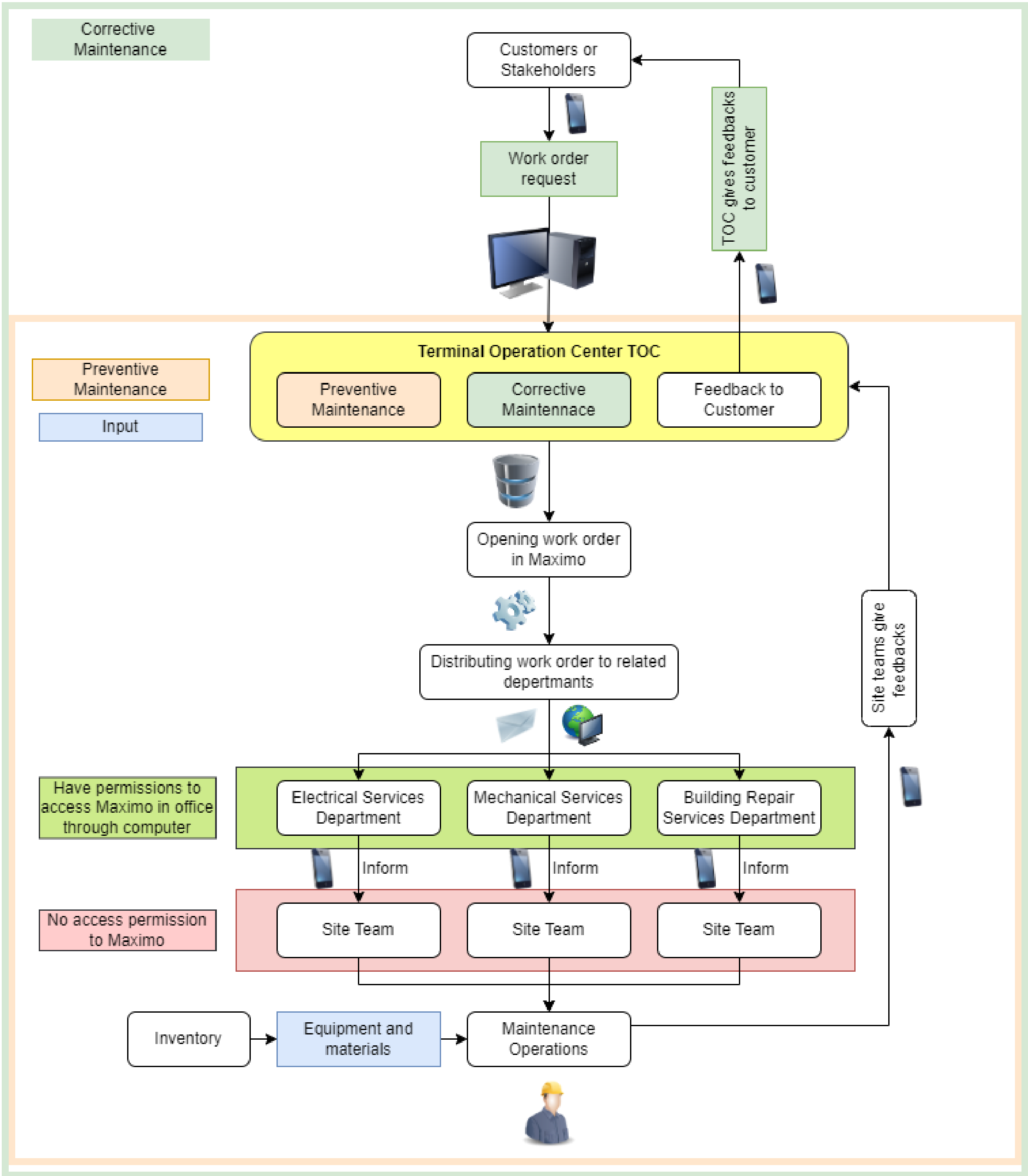

Figure 1: Maintenance process with Maximo.

In the context of corrective maintenance, passengers or stakeholders typically report any issues regarding malfunctioning assets to the Terminal Operations Center (TOC). Once notified, the TOC will create a corrective maintenance work order on Maximo and initiate the maintenance procedure. The work orders are automatically sent to the relevant departments, which then forward these work orders to relevant site teams via phone. After completing the maintenance task, the site team gives feedback to the TOC by phone, and the work order is closed based on this information (e.g., parts used and time spent). This exchange of information is fragmented, i.e., problem description shared through photos or documents to the TOC, delivery of work orders to field teams via phone, and the subsequent communication of maintenance repair actions to the TOC via phone. It is crucial to acknowledge that the lack of an integrated CMMS tool and the circulation of information in this manner poses risks to the maintenance work cycle. In particular, deficiencies in the information exchange process lead to incomplete, fragmented, and inaccurate data circulation.

Work orders for preventive maintenance are automatically created by Maximo at a designated frequency based on meter or time, depending on the instructions in the manufacturer's manuals and information entered into the program. For instance, if the conveyor system is used frequently and experiences heavy loads, TOC personnel may adjust the frequency of maintenance activities to occur more frequently based on meter-based readings such as total operating hours or distance travelled by the system. Conversely, if the conveyor system is used less frequently, the frequency of maintenance activities may be adjusted based on time-based readings, such as a fixed calendar schedule.

The CMMS capabilities, such as tracking maintenance schedules and managing inventory, can help airports streamline their operations and reduce downtime, which is crucial for airports hosting high volumes of passengers. Also, keeping a suitable inventory of resources is a key component of airport asset management. One of the significant challenges is the possibility of equipment warranties expiring, along with the end of manufacturers' support for equipment repair and spare parts. The airport operators must act proactively in these circumstances to ensure the continuation of operations by either stocking spare parts or updating the system before the production of the relevant spare parts comes to an end.

Asset Registration

In the case study, asset information is stored in three different systems: MS Excel, Oracle ERP software, and Maximo CMMS software. For asset registration, an internal coding system with a hierarchical ID structure can consist of different digits and hierarchies without reference to global or local standards. Each software platform (Excel, Oracle ERP, and Maximo CMMS) assigns the same asset with a different identity via a unique identification. For example, the asset inventory and coding system were formulated within Excel spreadsheets and stored locally on a computer (Figure 2). The coding structure comprises six hierarchical levels. Initially, each asset is assigned a unique Row Number, progressing sequentially from 1 to the list's end. Subsequently, assets are categorized into six main groups: (1) Electric-Electronic Systems, (2) Mechanical Systems, (3) Mechanical Installation, (4) IT Systems, (5) Build-Repair, and (6) Others. Within these groups, various sub-categories are delineated; for instance, under Mechanical Systems, sub-categories include (01) 400 Hz Electrical Systems, (02) Elevators, and (03) Baggage Handling Systems. Each asset is then assigned a sequential equipment number, followed by the supplier code, and concludes with the acquisition date in Month-Year format.

On the other hand, the Asset ID is usually generated according to a predetermined numbering system established within Maximo (Figure 2). This system can be customized to incorporate alphanumeric characters, as well as prefixes and suffixes tailored to the organization's requirements. For instance, an Asset ID could comprise a site code, a type code, and a sequential number. Thus, an Asset ID for an elevator at Site A may appear as "A-ELEVATOR-001".

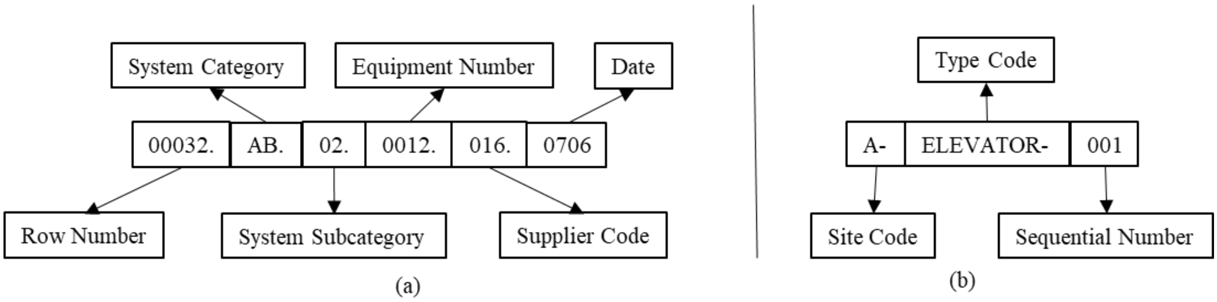

Figure 2: An asset code for a terminal block service lift code (MS Excel) (a) and for an elevator in Site A (Maximo) (b).

The absence of a unified asset tracking and management system makes asset identification inconsistent, which hinders the streamlined processing and analysis of gathered data in the airport and across multiple airports that are operated by the parent company. The findings demonstrated that there is a need for standardizing asset identifiers across various software systems used in the facilities management of airports for data integration and analysis and for improving overall asset management efficiency. Standardized asset classification and registration procedures provide consistency among all managed airports, enabling more efficient asset tracking and maintenance procedures in various settings. These findings highlight the importance of an appropriate classification scheme for effective building asset management.

Procedures and Standards

ISO 55001 offers enterprises a framework for managing their assets more efficiently, with its instructions for creating an asset management system that aligns with the company's strategic goals and emphasizes continual improvement in asset management procedures (ISO 55000, 2014). In the investigated case study, the interviewed experts were unaware of ISO 55000 asset management standards, and neither a national nor an international asset management standard was used. One of the experts stated that they were going to sign a new contract with the airport state authority for an extension of airport operation, and they were searching for a different asset management approach in the following years. Overall, a lack of clear guidance or standards on asset management at airports can cause several problems, such as inefficient asset management, not aligning with strategic objectives, reduced compliance with requirements, and decreased safety of the environment.

Conclusions

This study explored airport asset management practices through a case study at a large-scale airport, offering valuable insights into asset management processes. Critical assets requiring close monitoring for successful airport operation were identified, and the preference for powerful preventive maintenance tools (such as Maximo) in large airports was emphasized due to their complex infrastructure. It was identified that the absence of integrated on-site CMMS tools and interoperability issues between financial tools-ERP systems and CMMS tools-databases pose challenges. Inconsistent asset tracking and management systems hinder efficient data processing and analysis, emphasizing the need for standardized practices both within the airport and across multiple airports managed by the same operator company. Efficient spare parts management is essential for uninterrupted maintenance activities. While ISO 55000 standards are highly recommended for airports, the conducted case study revealed a lack of awareness and utilization of these standards. Implementing comprehensive training programs, interactive workshops, clear communication channels, and professional development opportunities linked to ISO 55000 can equip airport staff with the necessary knowledge and skills, fostering a culture of awareness, engagement, and continuous improvement in asset management. The study's findings can guide researchers in developing frameworks and practitioners in enhancing asset management processes. Future research could extend to various airports to explore diverse critical assets, digital tools, asset maintenance procedures, asset registration practices, and used procedures and standards.

References

Abdelhamid, M. S., Beshara, I., & Ghoneim, M. (2015). Strategic asset management: Assessment tool for educational building in Egypt. *HBRC Journal*, *11*(1), 98-106.

Al-Kasasbeh, M., Abudayyeh, O., & Liu, H. (2020). A unified work breakdown structure-based framework for building asset management. *Journal of Facilities Management*, *18*(4), 437-450.

Becerik-Gerber, B., Jazizadeh, F., Li, N., & Calis, G. (2012). Application areas and data requirements for BIM-enabled facilities management. *Journal of Construction Engineering and Management*, 138(3), 431-442.

Bertolini, L., Ciampoli, L. B., Pinto, R., & Benedetto, A. (2023, October). Survey of airport facilities: novel approaches. In *Earth Resources and Environmental Remote Sensing/GIS Applications XIV* (Vol. 12734, pp. 202-210). SPIE.

Denicol, J., Davies, A., & Pryke, S. (2021). The organisational architecture of megaprojects. *International Journal of Project Management*, *39*(4), 339-350.

Dixit, M. K., Venkatraj, V., Ostadalimakhmalbaf, M., Pariafsai, F., & Lavy, S. (2019). Integration of facility management and building information modeling (BIM) A review of key issues and challenges. *Facilities*, *37*(7/8), 455-483.

Hein, D. K. (2014). Key components for the effective management of airport assets. In *T&DI Congress 2014: Planes, Trains, and Automobiles* (pp. 869-881).

International Organization for Standardization. (2018). *Asset management — management systems, Guidelines for the application of ISO 55001*, (ISO Standard No. 55002:2018).

Kelly, G., Serginson, M., Lockley, S., Dawood, N., & Kassem, M. (2013, October). BIM for facility management: a review and a case study investigating the value and challenges. In *Proceedings of the 13th international conference on construction applications of virtual reality* (Vol. 5).

Keskin, B., Salman, B., & Koseoglu, O. (2022). Architecting a BIM-based digital twin platform for airport asset management: a model-based system engineering with SysML approach. *Journal of Construction Engineering and Management*, *148*(5), 04022020.

Kong, D., Kapogiannis, G., & Cheshmehzangi, A. (2022). Smart Airport: Mobile Asset Information Modeling Management based on Gamificative VR Environment---A Case Study of Ningbo Lishe International Airport Staff Restaurant. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1048, No. 1, p. 012009). IOP Publishing.

Koseoglu, O., Keskin, B., & Ozorhon, B. (2019). Challenges and enablers in BIM-enabled digital transformation in mega projects: The Istanbul new airport project case study. *Buildings*, *9*(5), 115.

Kula, B., & Ergen, E. (2021). Implementation of a BIM-FM platform at an international airport project: Case study. *Journal of Construction Engineering and Management*, *147*(4), 05021002.

Liu, R., & Issa, R. R. (2013). Issues in BIM for facility management from industry practitioners' perspectives. In *Computing in Civil Engineering (2013)* (pp. 411-418).

Liu, R., & Zettersten, G. (2016). Facility sustainment management system automated population from building information models. In *Construction Research Congress 2016* (pp. 2403-2410).

Munir, M., Kiviniemi, A., & Jones, S. W. (2019). Business value of integrated BIM-based asset management. *Engineering, Construction and Architectural Management*, *26*(6), 1171-1191.

Neath, S., Hulse, R., & Codd, A. (2014, May). Building information modelling in practice: transforming Gatwick airport, UK. In *Proceedings of the Institution of Civil Engineers-Civil Engineering* (Vol. 167, No. 2, pp. 81-87). Thomas Telford Ltd.

Parsanezhad, P., & Dimyadi, J. (2013). *Effective facility management and operations via a BIM-based integrated information system.*

Pascarella, D., Gigante, G., Vozella, A., Bieber, P., Dubot, T., Martinavarro, E., ... & Li Calzi, G. (2022). A methodological framework for the risk assessment of drone intrusions in airports. *Aerospace*, *9*(12), 747.

Roda, I., & Macchi, M. (2018). A framework to embed Asset Management in production companies. *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*, *232*(4), 368-378.

Saunders, M., Lewis, P., & Thornhill, A. (2009). *Research methods for business students*. Pearson education.

Shah, R., McMann, O., & Borthwick, F. (2017). Challenges and prospects of applying asset management principles to highway maintenance: A case study of the UK. *Transportation Research Part A: Policy and Practice*, *97*(17), 231–243.

Velmurugan, R. S., Dhingra, T., & Velmurugan. (2021). *Asset Maintenance Management in Industry*. Springer International Publishing.

Yin, R. K. (2018). *Case study research and applications* (Vol. 6). Thousand Oaks, CA: Sage.

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