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Digital Transformation Process in the Construction Sector and the Role of Artificial Intelligence

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ABSTRACT
This study aims to examine the digital transformation process in the construction sector from a holistic perspective, addressing all phases of the project lifecycle, including smart city applications, and to explore the role of artificial intelligence within this transformation. The research adopts a qualitative methodology, employing descriptive content analysis and document analysis techniques. A total of 201 documents were reviewed, and 41 were selected through purposive sampling for in-depth analysis. The findings reveal that technologies such as Building Modelling Information, Internet of Things, Artificial Intelligence, and Digital Twins offer substantial benefits in areas including design accuracy, predictive maintenance, health and safety management, and sustainability monitoring. Additionally, the study highlights the shift from physical to cyber security in digital projects and the growing importance of government-led digital infrastructure and training programs for inclusive transformation. Cloud-based software platforms, tax incentives, and digital literacy programs are recommended to support small and medium-sized enterprises' integration into smart city projects. Artificial intelligence-based applications are found to significantly enhance resource management, sustainability strategies, and operational reliability in construction.

1. Introduction

Reducing digital transformation to the mere acquisition of technological devices and focusing solely on technology investments may lead to unsuccessful outcomes. Therefore, before embarking on a digital transformation journey, it is essential for a business to evaluate which stages of its operational processes and which organizational resources can provide meaningful data, along with the appropriate methods for data collection. Following this evaluation, several aspects should be considered: which technological tools will be employed for data collection, where the data will be stored, what technologies will be used for analysis, and how cybersecurity measures will be implemented. Through such a tailored approach, the digital transformation process can be aligned with the structural characteristics of the business much like a custom-fitted garment tailored specifically to its wearer. At every stage of this transformation, the influence of artificial intelligence (AI) is strongly evident. The increasing power of AI in digital transformation enables businesses to gain a clearer perspective on future operations based on historical data (Yoşumaz, 2024a; Yoşumaz & Uzun, 2024).

Recent studies on digital transformation in the construction sector highlight significant technological advancements. In this context, the academic literature reflects a wide range of investigations. Kazeem, Olawumi, and Osunsanmi (2023) explored the impact of AI on construction processes, while Bang and Andersen (2022) addressed its influence on sustainability within construction. Sacks, Girolami, and Brilakis (2020) examined the interplay between building information modeling (BIM) and AI in construction practices. Siccardi and Villa (2023) analyzed the emerging trends in the use of internet of things (IoT), BIM, and digital twin (DT) technologies within the sector. Johansson and Roupé (2024) studied virtual reality (VR) and its integration with BIM, and Seyman Guray and Kismet (2023) conducted a comprehensive review on the use of VR and augmented reality (AR) in construction. Wu, Wang, and Wang (2016) examined the application of 3D printing technologies in the construction sector and identified several critical limitations, including material constraints, scale and size restrictions, slow printing speeds, concerns regarding structural durability and safety, lack of standardized regulations, insufficient technical expertise within the workforce, and high initial costs.

These factors have hindered the widespread adoption of the technology within the industry. However, more recent developments indicate that some of these limitations are being gradually overcome. For instance, as reported by Swinhoe (2023), a data center being constructed in Germany using 3D printing technology demonstrates significant advancements in material engineering and structural reliability. This project can be considered noteworthy as it illustrates the feasibility of applying 3D printing technology in complex and large-scale infrastructure projects while meeting durability and safety standards. Nevertheless, challenges such as cost optimization and workforce training remain, particularly posing barriers for small firms in the sector to engage with such technologies in construction activities. Rane (2023) revealed the positive effects of BIM applications and AI integration on cost, quality, and occupational safety in construction projects. Similarly, Saleh, Elhendawi, Darwish, and Farrell (2024) emphasized the combined use of AI, BIM, and IoT in shaping smart and sustainable urban environments. Fan et al. (2021) proposes a comprehensive framework under the concept of Disaster City Digital Twin, which integrates AI with human decision-making to improve disaster preparedness, response, and recovery. Turk et al. (2022) emphasize the growing importance of cybersecurity in the digital transformation of the construction sector, highlighting a shift in focus from traditional physical security toward comprehensive cyber protection on construction sites.

In this context, this study is concerned with the comprehensive examination of digital transformation in construction projects across all phases of the project lifecycle, but also aims to investigate how AI is influencing the scope and direction of digital transformation initiatives in the construction sector. In this context, the following research questions will be addressed.

RQ1. How can the digital transformation process be structured in the construction sector?
RQ2. What is the role of artificial intelligence in the digital transformation of the construction sector?

2. MATERIALS AND METHODS

In order to address the research questions posed in this study, qualitative analysis methods including descriptive content analysis and document analysis were employed. Within the scope of the research, a total of 201 documents were reviewed using the keywords "construction," "digital twin," "IoT," "artificial intelligence," "BIM," and "virtual reality" across the Scopus, Web of Science (WoS), and Google Scholar databases. These documents constitute the population of the study. From this population, 37 documents were selected through purposive sampling to form the study sample. Details regarding the selected sample are presented in Table 1. In addition, information obtained from various websites was also utilized to support the case studies in practical applications.

Table 1. Documents analyzed within the scope of the study sample.

No	Documents	Year
1	Generative Artificial Intelligence and Usage in Academia.	2025
2	Advancements and challenges in the application of artificial intelligence in civil engineering: a comprehensive review.	2024
3	A Framework for Leveraging the Incorporation of AI, BIM, and IoT to Achieve Smart Sustainable Cities.	2024
4	Real-world applications of BIM and immersive VR in construction.	2024
5	A Qualitative Research on the Awareness of Trend Technologies Used in Digital Transformation of Businesses Across G20 Countries.	2024
6	The Relationship Between Industry 5.0 Process and ESG Process: A Qualitative Analysis in the Context of Türkiye's BIST Sustainability 25 Index White Good Sector	2024
7	An Examination of Cyber Security Solutions in Public and Private IaaS Infrastructures	2024
8	Project success and critical success factors of construction projects: Project practitioners' perspectives.	2023
9	Integrating Building Information Modelling (BIM) and Artificial Intelligence (AI) for Smart Construction Schedule, Cost, Quality, and Safety Management	2023
10	Trends in Adopting BIM, IoT and DT for Facility Management: A Scientometric Analysis and Keyword Co-Occurrence Network Review	2023
11	Investigating the Use of ChatGPT for the Scheduling of Construction Projects	2023
12	VR and AR in construction management research: bibliometric and descriptive analyses.	2023
13	An In-Depth Survey Demystifying the Internet of Things (IoT) in the Construction Industry: Unfolding New Dimensions.	2023
14	Construction Robotics: From Automation to Collaboration	2023
15	An Overview of Drone Applications in the Construction Industry	2023
16	Artificial Intelligence Methods for the Construction and Management of Buildings.	2023
17	Disaster City Digital Twin: A vision for	2023

	integrating artificial and human intelligence for disaster management.	
18	Design and Construction of A Bunut Oven Based on Artificial Intelligence.	2022
19	Smart Contracts and Supply Chain Management Using Blockchain	2022
20	Exploring the thermal conditions in construction sites through IoT based methodologies.	2022
21	Big data analysis of the Internet of Things in the digital twins of smart city based on deep learning. *Future Generation Computer Systems*	2022
22	Sustainable Smart City to Society 5.0: State-of-the-Art and Research Challenges.	2022
23	Utilising Artificial Intelligence in Construction Site Waste Reduction.	2022
24	Governance, Standards and Regulation: What Construction and Mining Need to Commit to Industry 4.0.	2022
25	A systemic framework for addressing cybersecurity in construction.	2022
26	Artificial intelligence in the construction industry: A review of present status, opportunities and future challenges.	2021
27	The adoption of iot in the Malaysian construction industry: Towards construction 4.0.	2021
28	Roles of artificial intelligence in construction engineering and management: A critical review and future trends.	2021
29	Digital Twin: Enabling Technologies, Challenges and Open Research	2020
30	Sustainability and energy efficiency: Bim 6d. study of the bim methodology applied to hospital buildings. value of interior lighting and daylight in energy simulation	2020
31	Potentials of artificial intelligence in construction management.	2020
32	Building Information Modelling, Artificial Intelligence and Construction	2020
33	How Digital Information Transforms Project Delivery Models.	2019
34	7D BIM for sustainability assessment in design processes: A case study of design of alternatives in severe climate and heavy use conditions.	2019
35	Sustainability-driven structural design using artificial intelligence. *20th Congress of IABSE, New York City 2019: The Evolving Metropolis - Report*	2019
36	The efficient generation of 4D BIM construction schedules: A case study of the Nanterre 2 CESI project in France	2018
37	Beyond the third dimension of BIM: A systematic review of literature and assessment of professional views.	2018
38	CAD of human resource configuration in project scheduling for construction engineering applications.	2018
39	A critical review of the use of 3-D printing in the construction industry.	2016
40	Bir İnşaat Projesinin Evreleri ile Zaman ve Maliyet Analizinin Proje Yönetim Teknikleri Vasıtasıyla İncelenmesi.	2012
41	Green BIM: Successful Sustainable Design with Building Information Modeling. In *Indianalolis*	2008

To ensure the reliability of the study, the analytical approach, research procedure, and the reviewed documents were evaluated by three subject-matter experts. As part of this evaluation process, each expert was asked three structured questions, resulting in a total of nine responses. Consensus was achieved in eight of these responses, while one response reflected a disagreement. The expert who provided the dissenting opinion argued that the number of reviewed documents was insufficient. However, based on the other two experts' positive evaluations regarding the adequacy of the document count, no additional documents were included in the study. The reliability of the evaluation was calculated using the formula proposed by Miles and Huberman (1994, p. 64): Reliability = Agreement / (Agreement + Disagreement) = 8 / (8 + 1) = 0.88. Accordingly, the reliability ratio was determined to be 88%. The methodology and scope of the study are illustrated in Figure 1.

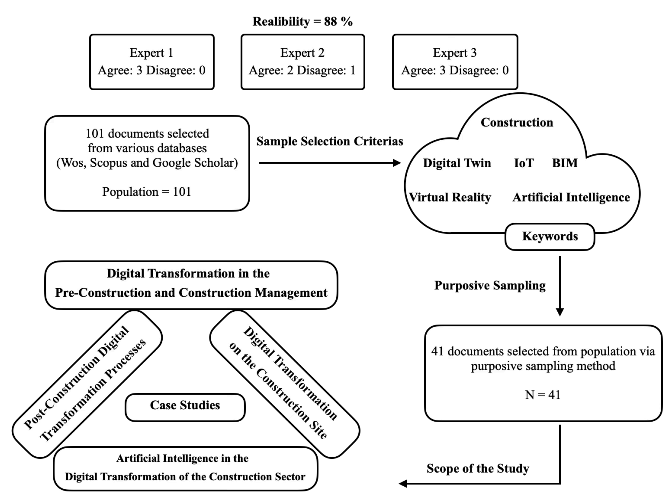

Figure 1: Scope of this Study

3. FINDINGS AND DISCUSSIONS

A. *RQ1. How Can the Digital Transformation Process be Structured in the Construction Sector?*

To address this research question, the digital transformation process within the construction sector was examined through a three-phase framework: pre-construction, on-site construction, and post-construction. Each phase encompasses distinct scopes, technologies, and methodologies, indicating that digital transformation in the construction industry is a staged, context-driven, and process-oriented progression. Furthermore, the analysis incorporated considerations of government policies and smart city initiatives, recognizing their influential role in shaping digital adoption. In particular, the study recommends the development of tailored digital tools and software solutions to support the transformation efforts of small-scale construction firms operating in the public sector, thereby enhancing inclusivity and capacity for digital integration across the industry.

The digital transformation process in the construction sector was analyzed by dividing it into three distinct phases (2023):

a) Digital transformation efforts during the pre-construction stage,

b) Digital transformation on the construction site,

c) Digital transformation in the post-construction stage

1) Digital Transformation in the Pre-Construction and Construction Management Stages

Within the scope of this study, the pre-construction phase encompasses budgeting, cost estimation, human resource planning, project scheduling, engineering analysis, procurement planning, design development, and architectural planning Coşkun & Ekmekçi (2012). These processes form the foundation of construction projects and play a critical role in determining overall project success. Effective management of these stages requires robust collaboration among all stakeholders, structuring the entire process based on data, and leveraging technology to utilize the gathered data as a catalyst for project efficiency Kumar et al. (2023; Whyte, 2019). One of the most prominent approaches in this context is the BIM system for project management. BIM enables the digital modeling of construction projects with a data-centric structure. It typically begins with traditional two-dimensional building drawings (BIM 2D). When material specifications, structural components, and geometric features are incorporated, the model becomes three-dimensional (BIM 3D) (Charef et al., 2018). The inclusion of a time dimension—enabling the scheduling of the project using data and knowledge—introduces the concept of BIM 4D (Doukari et al., 2022). When budget planning and cost estimation are added, the model evolves into BIM 5D (Mesároš et al., 2019). With sustainability considerations, it becomes BIM 6D, and with facility management integration, BIM 7D. Furthermore, when occupational health and safety are also incorporated, the model is referred to as BIM 8D (Andreani et al., 2019). Figure 2 illustrates how the dimensions of BIM correspond to different phases within the construction process. These dimensions, when integrated through one or more software solutions, form a comprehensive BIM framework.

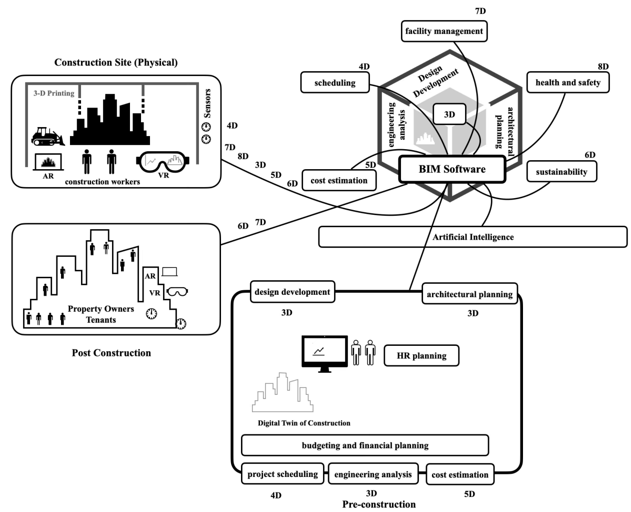

Figure 2: BIM Dimensions and Relation of Construction Processes (Source: Author's own work)

Engineering analysis and design development form the technical foundation of pre-construction processes, where digital technologies bring significant advancements. In engineering analysis, simulation software and BIM are employed to assess parameters such as structural integrity, energy efficiency, and environmental impacts, thereby minimizing associated risks (Krygiel & Nies, 2008). During design development, AI enables rapid evaluation of multiple design alternatives, supporting solutions that are both functional and aesthetically appropriate. From an architectural planning standpoint, BIM's 3D modeling capabilities allow design teams to better visualize complex projects and enhance alignment with stakeholders. Additionally, digital tools support environmental sustainability objectives during the design phase by facilitating alignment with green building standards (Mathern et al., 2019; Sulandari et al., 2022; Yang et al., 2024).

Budget planning and cost estimation are key components in maintaining the financial sustainability of construction projects, and digital transformation offers significant advantages in this area. During the design phase, detailed analysis of material, labor, and other associated costs contributes to more reliable budget forecasting. AI-supported algorithms also improve the accuracy of future cost estimations by drawing insights from historical project data. Procurement planning, which involves the strategic management of materials and logistics prior to construction, is a critical element of budgeting and cost management (Abioye et al., 2021; Harle, 2024). When integrated with BIM, procurement systems leverage demand forecasting software to optimize inventory levels and prevent issues related to overstocking or shortages.

Moreover, BIM-integrated procurement systems can identify material needs during the design stage, helping to reduce waste and accelerate delivery processes (Rane, 2023; Saleh et al., 2024). In particular, blockchain technology strengthens transparency and traceability in the supply chain, enhancing the security and efficiency of material procurement. Blockchain-based digital contracts are emerging as a potential solution that may be incorporated into BIM processes to ensure transparency for all stakeholders (Siccardi & Villa, 2023; Singh & Prasath Kumar, 2022).

In human resource planning, digital platforms analyze team capabilities and workload distribution to enable optimal personnel allocation, which ensures that projects are assigned to appropriately qualified professionals (Lin et al., 2018; Prieto et al., 2023). Project scheduling processes benefit from BIM and integrated project management software by optimizing the sequencing and duration of tasks, thereby reducing delays. For instance, 4D BIM applications allow the visualization of project timelines, enabling early detection of scheduling errors. However, the effective implementation of such systems requires the widespread adoption of sector-specific training and the enhancement of digital skills among existing personnel. Consequently, the success of digitalization in human resources and scheduling processes depends on organizational adaptability and the digital proficiency of project teams (Doukari et al., 2022; Prieto et al., 2023). All processes integrated with BIM can also support the preparation of feasibility reports in construction projects. Such reports become more precise and predictable, thereby reducing the likelihood of project failure.

2) Digital Transformation on the Construction Site

Numerous technological developments are being employed as part of the digital transformation on construction sites. Technologies such as the IoT (Khurshid et al., 2023), Augmented Reality (AR), VR (Johansson & Roupé, 2024) (Seyman Guray & Kismet, 2023) 3-d printing (Wu et al., 2016), BIM, robotic automation (Parascho, 2023), drone technologies, and digital tools used to facilitate team collaboration (Choi et al., 2023; Parascho, 2023) are applied to improve site efficiency, support collaboration among teams, enhance safety protocols, and optimize project delivery timelines.

IoT, in particular, plays a vital role in operational efficiency through its real-time data collection and monitoring capabilities. During the digital transformation process, physical data can be transferred to digital environments via IoT infrastructure. IoT sensors monitor equipment performance, environmental conditions such as temperature and humidity, and worker safety continuously, thereby providing project managers with real-time data. This information contributes significantly to resource management and cost control during both the pre-construction and active construction phases. Data collected in real time supports the optimization of machinery maintenance schedules, material tracking, team coordination, accident prevention, and more efficient use of equipment on-site (Ibrahim et al., 2021; Khurshid et al., 2023). For example, sensors embedded in workers' vests allow remote monitoring and foster collaborative work environments. Figure 3 visualizes an example of a sensor-equipped vest used in IoT applications (Edirisinghe et al., 2022; Hiotron, 2019)).

Figure 3: Worker vest equipped with IoT (Hiotron, 2019)

In addition, the analysis of data transferred to digital environments is enhanced through AR and VR technologies, enabling field teams to comprehend complex projects better and conduct simulations before implementation. These technologies strengthen the technical capabilities of on-site personnel and contribute to reducing error rates (Johansson & Roupé, 2024; Seyman Guray & Kismet, 2023). AR facilitates the visualization of BIM models directly within the construction site, allowing for the immediate detection of structural inconsistencies. VR, on the other hand, offers virtual training environments for workers to engage in hazardous tasks, thereby improving safety standards. Given the labor-intensive nature of the construction sector, VR technology can significantly ease the integration of field teams into on-site processes. Figure 4 (BuildAustralia, 2023) shows an operator receiving on-the-job training through VR technology. Figure 5 (ArborXR, 2024) provides an example of AR usage in a construction setting.

Figure 4: An operator receiving on-the-job training with VR technology (BuildAustralia, 2023).

Figure 5: An example of the use of AR technology in construction (ArborXR, 2024)

One of the most striking aspects of digital transformation on construction sites is the integration of 3D printing technology. The adoption of 3D printing in construction environments introduces novel approaches to material usage and construction processes, along with the emergence of new business models. This technology is particularly effective in rapid prototyping and the production of modular structural components, serving as an alternative to conventional concrete casting methods. Among its most significant advantages are the reduction of construction waste, thereby contributing to environmental sustainability, the lowering of labor requirements and associated costs, the shortening of construction timelines, and the ability to rapidly generate construction prototypes (All3dP, 2021; Swinhoe, 2023; Wu et al., 2016). Furthermore, innovative designs enabled by AI technologies can be realized more efficiently through 3D printing. Figure 6 (Swinhoe, 2023) presents an example of a building produced with 3D printing technology, belonging to the Heidelberg IT Management company in Germany.

Figure 6: Heidelberg iT Management Building (Almanya) (Swinhoe, 2023).

Robotic automation represents another critical component of digital transformation on construction sites, laying the groundwork for enhanced collaboration between workers and machines. Robots are increasingly utilized to automate repetitive tasks such as bricklaying and concrete pouring, which contributes to reducing labor costs and improving safety by minimizing the need for human involvement in hazardous operations (Parascho, 2023). Figure 7 (Hilti, 2020) illustrates an example of a robot that automates drilling operations using a hammer drill.

Figure 7: A Cobot Hilti machine collaborating with an employee (Hilti, 2020).

Drone technology plays a role beyond site inspections, also contributing to material transportation by replacing manual processes in tasks such as the transport of small-scale loads, thereby saving time (Choi et al., 2023). Figure 8 shows an example of drone usage (NorthConstruction, 2023).

Figure 8: Drone use on the construction site (NorthConstruction, 2023).

In the pre-construction processes, data designed according to the BIM process is shared with workers, machines, and other equipment at the construction site, ensuring the seamless continuation of the construction process and enabling transparent monitoring of the progress in accordance with the project. Additionally, data collected during the construction phase via IoT technologies from both workers and equipment allows for the collaboration between machine and human at the construction site, working within the technology layer. When the processes across pre-construction, construction site, and post-construction stages are designed in a way that allows data acquisition, the AI of the construction project can be defined, making it possible to monitor all processes transparently (Fuller et al., 2020).

3) Post-Construction Digital Transformation Processes

Post-construction processes include facility management, maintenance and repair, energy efficiency analysis, and asset management. Facility management, being a core component of the post-construction process, benefits from significant innovations brought about by digital transformation. Within the BIM process, data obtained during the design and construction phases is transferred to facility management processes, allowing more efficient management of the maintenance and operational needs of the buildings (Siccardi & Villa, 2023). IoT sensors continuously track the real-time performance of building systems, including HVAC and lighting, allowing facility managers to identify potential failures early and enhance the efficiency of maintenance operations. IoT-based systems also track the condition of building elements (e.g., roofs, pipes), detecting issues such as wear and damage early on, providing maintenance teams with the opportunity for proactive intervention. BIM's 6D applications integrate maintenance plans with building data, making repair processes more planned and cost-effective. Furthermore, AI algorithms learn from past maintenance data to predict future repair needs and optimize resource allocation (Montiel-Santiago et al., 2020).

Performance monitoring and energy efficiency analysis are other key elements in post-construction processes that support sustainability goals. Using AI technology, energy consumption and natural resource usage can be tracked in real time, facilitating the development of energy efficiency and environmental sustainability strategies. AI technology can optimize energy efficiency by evaluating data from IoT sensors and adjusting energy usage within the building (Andreani et al., 2019; Siccardi & Villa, 2023). For example, lighting or heating system settings can be automatically adjusted. Additionally, smart irrigation systems around the building, when integrated with the AI infrastructure, can optimize water usage for landscaping outside the building by automating irrigation settings. The control units of smart irrigation systems transfer environmental data such as air temperature and soil moisture to the AI technology, ensuring that irrigation systems use water at optimal levels. Figure 9 provides an example of a control unit for smart irrigation (Rainbow, 2024).

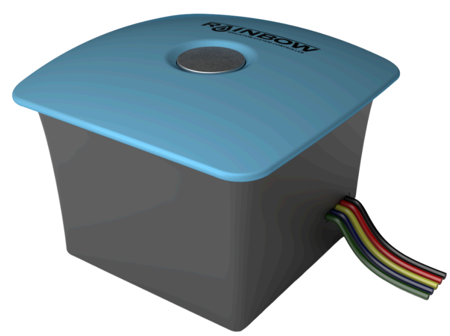

Figure 9: smart irrigation controller example (Rainbow, 2024)

4) Physical Security to Cyber Security

The widespread adoption of digital technologies in the construction sector has brought cybersecurity to the forefront as a critical issue that influences every stage of the industry's digital transformation process. Traditionally centered on physical security, the construction industry is now compelled to consider cybersecurity aspects such as data protection, system integrity, and the safeguarding of digital assets. Particularly in digital projects where AI and IoT systems are integrated, the development of protection strategies against cyberattacks has become an industry-wide necessity. IoT technologies enable the digital monitoring of equipment, material tracking systems, and worker safety solutions at construction sites. However, since these devices communicate over networks, they are continuously exposed to cybersecurity risks. Weak encryption, outdated software, or vulnerabilities in inter-device communication can lead to serious security breaches, such as data leakage or remote control of systems. Therefore, the use of IoT devices in construction sites necessitates the advance planning of both hardware and software security measures (Turk et al., 2022).

The security of the data used and trained by AI-based systems, and the potential for output manipulation due to inaccuracies in training data, further heighten cybersecurity risks in the sector. Another critical issue is the potential vulnerabilities in the code of cloud-based software commonly used in construction projects. Accordingly, the implementation of encryption protocols, activation of multi-factor authentication systems, and routine penetration testing to identify system weaknesses are essential during the deployment of such applications (Yoşumaz, 2024b).

Moreover, enhancing employees' digital awareness and providing fundamental cybersecurity training can contribute to reducing human-induced risks within the sector. Employing cybersecurity specialists, or where direct employment is not feasible, obtaining consultancy services from firms operating in this domain, is also considered crucial for the industry (Turk et al., 2022; Yoşumaz, 2024).

5) *Government Policies and the Smart City Process*

Digital transformation is becoming increasingly critical in the construction sector due to its potential to enhance operational efficiency, promote environmental sustainability, and reduce long-term costs (Abioye et all., 2021). However, this transformation process does not equally benefit all stakeholders in the sector. In particular, small and medium-sized enterprises (SMEs) face various structural and economic barriers in accessing and implementing digital technologies. While large-scale firms can more easily adopt such technologies due to their financial capacity and customer base, SMEs often lag behind in this transformation (Smith & Sepasgozar, 2022). Businesses involved in large-scale construction projects typically serve high-income clientele, allowing them to pass on the additional costs associated with digital solutions to end users. In contrast, the target audience of small and medium-sized construction companies often consists of individuals or small businesses with limited financial resources. When the costs of digital transformation are directly transferred to these customers, it may reduce the appeal of such projects and hinder firms' willingness to invest in digital technologies. Particularly in social housing developments, small-scale industrial zones, or low-cost housing projects, the cost of integrating digital technologies tends to extend the return on investment and raises questions about cost-effectiveness. In this context, public policies play a pivotal role in guiding and incentivizing the digital transformation process. To ensure the integration of SMEs into this transformation, state-supported strategies must be developed (Smith & Sepasgozar, 2022). These strategies should aim both to facilitate access to technological infrastructure and to enhance the digital competencies of the workforce. The following policy instruments are proposed to support this objective:

a) Publicly supported digital infrastructure and software: Cloud-based software platforms with simplified user interfaces that incorporate BIM infrastructure can be developed by governments for use by SMEs. Such applications would allow firms to efficiently and cost-effectively manage processes such as digital data processing, energy efficiency assessments, project monitoring, and resource planning.

b) Financial incentives: Financial tools such as tax reductions, low-interest loan programs, or digitalization grants can be introduced for SMEs that develop construction projects aligned with smart city solutions. These supports would increase the motivation of firms to invest in digital technologies (Smith & Sepasgozar, 2022).

c) Digital training and certification programs: Effective use of digital technologies requires the development of sector-specific knowledge and skills. Government-supported vocational training centers or online platforms can offer training on technologies such as BIM, the Internet of Things (IoT), AI, and DTs. In Türkiye, for example, digital literacy programs offered for free through platforms like BTK Academy could be tailored to the needs of the construction sector and made accessible to a broader audience (BTK Academy, 2025).

d) Environmentally focused digital practices: The use of digital tools by SMEs for monitoring carbon emissions, analyzing energy consumption, and planning eco-friendly materials can significantly reduce the environmental impact of the construction sector. Firms adopting such practices can be rewarded with green building certifications, eco-labels, or sustainability incentives. These initiatives could be further strengthened by combining them with financial support mechanisms (Adekanye et all., 2020).

Digital transformation not only contributes to economic and environmental outcomes but also offers critical benefits in the areas of disaster management and public safety. Smart city planning is a fundamental driver of the direction of digital transformation in the construction sector, closely tied to government policies, and environmental sustainability is an integral part of this vision. Governments' smart city visions require the integration of technologies such as IoT-based monitoring systems, DTs, and cloud-based platforms into construction processes, ensuring that cities achieve targets like energy efficiency, security, and carbon neutrality. From an environmental sustainability perspective, government policies aimed at reducing carbon emissions and promoting green building standards strengthen the potential of digital technologies to optimize environmental impacts. Additionally, if building wear and tear can be monitored through sensors, governments can act swiftly during reconstruction after events like earthquakes (Li et al., 2022; Mishra et al., 2022). In particular, DT technology presents significant opportunities to enhance disaster resilience in the built environment—an area that has yet to be fully leveraged. Fan et al. (2021) propose a comprehensive framework under the concept of Disaster City Digital Twin, which integrates AI with human decision-making to improve disaster preparedness, response, and recovery. The study emphasizes four critical components: multi-source data sensing, data integration and analytics, multi-actor decision-making via game theory, and dynamic network analysis—all essential for developing real-time, responsive urban systems. By establishing real-time virtual replicas of physical infrastructure, DTs enable continuous monitoring, predictive analysis, and simulation of structural behavior under extreme conditions such as floods or earthquakes. This functionality not only supports proactive maintenance and rapid emergency response but also facilitates coordination among stakeholders during crises.

B. *RQ2: What is the role of artificial intelligence in the digital transformation of the construction sector?*

To address this research question, the role of AI in the digital transformation of the construction sector was examined holistically across the pre-construction, construction, and post-construction phases. AI technologies, such as machine learning, deep learning, natural language processing, and big data analytics, contribute significantly to the digitalization of construction processes by enhancing design optimization, operational efficiency, risk management, and predictive maintenance.

The rapid rise of AI technologies since the end of 2022 (Yoşumaz, 2024a) has started to show its impact in the construction sector, as in all other industries. However, as with other sectors, the impact initially begins with large businesses and gradually spreads to smaller businesses, depending on the speed of technological advancement. Therefore, the adoption of AI technologies, and many other technologies related to digital transformation, initially starts with large businesses.

Historical data plays a significant role in leveraging AI technologies. In this context, construction businesses with experience from numerous projects can analyze past data with AI algorithms, resulting in more sustainable designs, cost-effective construction projects, and buildings free from previous errors (Yoşumaz, 2025).

AI technologies, including big data analytics, machine learning, deep learning, and natural language processing, can be used in a wide range of activities within construction projects, from planning, design, and management to construction site operations, health and safety, and facility management (Yoşumaz, 2024a).
In the pre-construction phase, AI contributes to the design process through generative design applications, which allow for rapid development of multiple design alternatives, enabling early evaluations of various options. The most suitable design can then be refined and utilized (Eber, 2020; Sacks et al., 2020).

In feasibility studies for construction projects, potential budget overruns, schedule delays, and structural risks can be anticipated through the analysis of historical data, thereby enhancing planning accuracy and facilitating improved coordination among stakeholders (Ivanova et al., 2023; Sacks et al., 2020). Within this context, software applications utilizing advanced natural language processing models, including transformer-based architectures such as the generative pre-trained transformer model (GPT), have been increasingly employed to support various construction project processes. These applications enable automated analysis and summarization of documents, detection of risks and anomalies in textual reports, as well as interactive question-answering systems that provide real-time technical guidance to project teams. However, it should be noted that GPT like ChatGPT may not be specifically trained on data from the construction domain. Therefore, it is recommended to use software solutions specifically developed for the construction industry, based on natural language processing models tailored to this sector, to ensure greater accuracy and applicability in practice (Prieto et al., 2023).

AI-supported BIM applications make it possible to test construction designs before the actual construction process begins. By facilitating analysis and simulation through machine learning models such as random forest, support vector machines, and artificial neural networks, these applications enable more accurate risk assessment and design optimization. This ensures that projects are thoroughly tested prior to implementation, thereby reducing errors and optimizing environmental impacts (Sacks et al., 2020). Unlike traditional BIM, which primarily serves as a static information repository and coordination tool, AI-enhanced BIM dynamically interprets data, learns from previous projects, and continuously improves decision-making processes throughout the construction lifecycle.

On construction sites, AI plays a significant role in coordinating operations, managing resources, monitoring health and safety, and enabling real-time decision-making. By analyzing historical project data, AI can optimize resource allocation, reduce waste, and efficiently plan the use of construction equipment. Pilot implementations reported by Bang and Andersen (2022) demonstrate that AI-supported image recognition systems, utilizing data from drones and fixed cameras, effectively monitor construction progress and identify safety violations, such as workers not wearing helmets. These pilot applications have shown promising results in improving site safety compliance and operational efficiency, although further large-scale deployments are needed to validate their broader effectiveness (Bang & Andersen, 2022; Pan & Zhang, 2021).

In post-construction processes, AI technologies are also used in facility management. Data from equipment such as HVAC systems, energy systems, and smart irrigation systems can be analyzed to optimize energy consumption, natural resource usage, and maintenance (Zhang et al., 2022). For example, sensors placed in roofing materials and pipes can predict wear and tear, leading to long-term cost savings in management. Furthermore, AI-supported DTs built throughout the lifecycle of a building allow for transparent and proactive facility management (Hakimi et al., 2024).

One of the prominent applications of AI in the construction industry is predictive maintenance. Data collected from machinery and equipment used on construction sites are analyzed through AI-supported software to enhance operational efficiency. In this context, the HVI Smart Maintenance Solution developed by Caterpillar has successfully reduced the downtime of excavators by 40% through predictive analysis, demonstrating that AI-based systems enable proactive intervention before failures occur. The system continuously monitors machine operating hours in real time, detects excessive usage, and facilitates timely preventive maintenance. It also performs automated diagnostics by analyzing Diagnostic Trouble Codes (DTCs), particularly those related to hydraulic pressure, enabling early identification of recurring issues. Furthermore, HVI uses AI-driven workflows to dynamically adjust maintenance schedules based on actual equipment usage, ensuring servicing aligns with real wear conditions rather than arbitrary time intervals. In addition, it streamlines spare parts management by automatically generating work orders, identifying and reserving required components, and issuing purchase requisitions to avoid inventory shortages, thereby enhancing the overall effectiveness of maintenance operations (HVI, 2025.

AI has increasingly come to be regarded not merely as an innovation tool but as a strategic technology that fundamentally transforms operational processes within the construction industry. This transformation was comprehensively addressed in an interview titled “AI Makes Its Construction Debut” on the Bridging the Gap Podcast, featuring Patrick Murphy, CEO of Togal.AI. According to Murphy, one of the primary contributions of AI lies in its capacity to analyze large datasets in real time and generate predictive models. This capability enables construction firms to identify potential risks before they materialize, optimize resource utilization. In particular, AI-based solutions have been noted to improve accuracy in processes such as time and cost estimation, thereby enhancing the reliability of decision-making. In this context, AI to promote the circular economy within construction. AI can enable more efficient resource management by predicting material demand and optimizing the reuse and recycling of construction waste, thereby reducing environmental impact and supporting sustainability goals. Another noteworthy aspect highlighted in the interview is AI systems’ ability to learn from data derived from past projects. Murphy asserts that this learning process allows AI to recognize patterns that may be overlooked by human observation, significantly reducing error rates. However, the effective integration of these technological advancements into the construction sector is directly linked not only to software infrastructure but also to organizational and cultural transformation. As emphasized by Murphy, a major obstacle to this transition is the low level of digital literacy among field personnel and mid-level technical staff. Additionally, concerns related to the implementation and maintenance costs of AI systems, along with data privacy issues, pose substantial challenges to full adoption. Despite these difficulties, from Murphy’s perspective, the inevitability of AI becoming an indispensable component of the sector appears unquestionable. Within this context, it is recommended that firms invest in training programs focused on enhancing digital competencies and update traditional project management approaches by adopting agile methodologies. According to Murphy’s evaluation, AI is positioned not as a substitute for human labor but as a complementary tool that supports decision-making processes. This approach establishes an integrative collaboration between technology and human effort, enabling the incorporation of data-driven and highly accurate processes into the construction industry.

Murphy's evaluations suggest that although there are various challenges in integrating artificial AI into construction operations, the transformative potential of this technology is expected to significantly influence the sector's financial prospects. As the technology matures and adoption barriers are overcome, the construction industry is entering a substantial growth phase driven by AI-based innovations. This global expansion is clearly reflected in market dynamics, with varying AI adoption rates and investments across regions, particularly prominent in key markets such as North America and the Asia-Pacific. The global use of AI in the construction sector reached a value of USD 3.06 billion in 2023 and is projected to increase to USD 3.98 billion in 2024. The market is anticipated to accelerate at a compound annual growth rate (CAGR) of 34.67% from 2024 to 2031, reaching USD 31.98 billion by 2031. The North American region held a significant market share of USD 1.18 billion in 2023, driven by its advanced technological infrastructure and widespread adoption of AI solutions in construction. Smart city initiatives, large-scale infrastructure investments, and green building projects in the United States and Canada support AI applications such as predictive analytics, autonomous equipment, and cloud-based project management, enhancing efficiency, safety, and sustainability. Moreover, the region's robust AI developer and startup ecosystem accelerates the diffusion of innovative solutions tailored to construction firms.

Conversely, the Asia-Pacific region exhibits the highest CAGR of 36.68% in AI usage, driven by rapid urbanization, labor shortages, and increasing project complexities in countries such as China, India, and Southeast Asian nations. It is expected to reach a competitive level with North America by 2031. Large-scale infrastructure investments, smart city developments, and renewable energy projects by regional governments constitute key factors fostering AI adoption. Additionally, the proliferation of cost-effective AI solutions and cloud technologies enables construction firms to rapidly integrate advanced technologies such as automation, predictive maintenance, and safety monitoring. This dynamic and rapidly evolving environment positions the Asia-Pacific region as one of the global leaders in AI-driven transformation within construction practices (King Research, 2024).

4. EVALUATON AND CONCLUSION

The digital transformation process in the construction sector signifies a paradigm shift through the integration of advanced technologies such as BIM, IoT, AI, and DTs, aiming to improve operational efficiency, reduce costs, and support sustainability objectives. This study has examined the multifaceted functions of these technologies across the pre-construction, construction, and post-construction phases, emphasizing both their transformative capacities and the challenges encountered during their implementation.

A. *Theoretical Contributions*

This research contributes to the academic literature by proposing a holistic and process-oriented framework that structures digital transformation into three distinct but interconnected stages. It extends existing studies by illustrating how BIM from 2D to 8D and AI-driven data analytics can optimize decision-making throughout the construction lifecycle. Furthermore, the study addresses a critical gap by positioning public policy, smart city initiatives, and sectoral digital transformation within an integrated framework. This approach underscores the need for inclusive and scalable digitalization strategies, particularly for SMEs, which face structural and financial barriers in technology adoption.

B. *Practical Implications*

This study emphasizes that technologies such as DTs facilitate predictive maintenance and real-time monitoring, which are critical for long-term asset management. AI applications, particularly in image recognition and generative design, enhance on-site safety and accelerate the development of sustainable structural models. However, the widespread adoption of these technologies requires not only substantial financial investments but also the development of skilled human capital and adaptive organizational structures.

The role of AI within the construction sector is particularly transformative. AI's capability to process historical data and produce predictive insights strengthens decision-making processes in areas such as design optimization, risk management, and resource allocation. For example, AI-assisted image recognition systems contribute to on-site safety improvements, while generative design tools facilitate the rapid development of sustainable structural models. These developments underscore the importance of prioritizing workforce training initiatives and enhancing organizational adaptability to fully leverage the potential of digital transformation.

Figure 9 visualizes the digital transformation in the construction sector, depicting the integrated application of advanced technologies throughout all phases of construction projects.

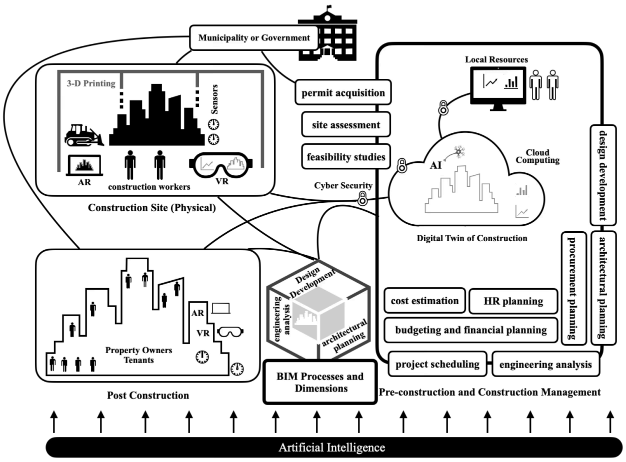

Figure 9: Digital Transformation Process in Construction Sector (Source: Author's own work)

This study provides a comprehensive overview of digital transformation practices in the construction sector; however, several areas merit further investigation. Future research could address the socio-technical challenges surrounding technology adoption, including resistance to organizational change and the ethical implications associated with AI applications in construction. Furthermore, empirical studies are necessary to quantify the long-term economic and environmental impacts of digital technologies, particularly within varying geographical and regulatory environments. The establishment of standardized frameworks for integrating emerging technologies into existing project workflows would also contribute to broader adoption across the sector.

In conclusion, digital transformation in the construction sector represents a fundamental shift in how projects are conceived, executed, and maintained. Beyond technological adoption, it requires strategic collaboration between businesses, policymakers, and academic institutions to overcome financial, technical, and cultural obstacles. The insights presented in this study provide a structured roadmap for leveraging digital technologies to promote efficiency, sustainability, and resilience in the construction of future urban environments.

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