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Assessing the Digital Transformation Readiness of the Construction Industry Utilizing the Delphi Method

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Abstract: The rapid advancement of digital technology has enabled digital transformation across various sectors, including construction. The construction industry has long been associated with conventional, labor-intensive practices that can adversely influence the entire construction process. However, this culture is changing as key players in the sector are progressively identifying and embracing the vast opportunities and associated benefits of using digital tools and technologies to improve the performance and outcomes of the overall project lifecycle. To this end, this study uses the Delphi technique to identify 70 factors that contribute to the digital transformation of the construction industry, categorizing them into five groups: management, design, technology, policy, and infrastructure. Delphi analysis is used to examine the critical success factors for digital transformation identified in the literature and rate their importance during the preconstruction, construction, and facility management phases. Furthermore, this research results in the introduction of the Digital Transformation Level of Readiness Framework (DTRLF) to help facility management firms, clients, organizations, contractors, and designers comprehend the implementation of digital transformation within their respective domains and support decision-makers in establishing action to adapt related technologies in their respected project phases.

Keywords: digital transformation; Delphi technique; construction sector digitalization; digitization; preconstruction; construction; facility management; infrastructure

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1. Introduction

The construction industry is facing a transformational shift as the world moves toward digital transformation in all sectors of the global economy. While the construction industry involves a variety of data exchange and stakeholder requirements, an important digital shift has resulted from the emergence of digital technologies, which have enhanced the digital transformation in construction as a whole. The digital transformation concept has increasingly gained traction in the construction sector, with the aim of upgrading or completely changing traditional construction practices to align with the demands of the digital age. Ref. [1] defines digital transformation as a procedure that combines information, storage, communication, and networking technologies to bring about a paradigm shift in services by replacing manual processes with digital processes, or by upgrading outdated digital technology to more recent iterations. Research has shown that digital transformation has the potential to influence any industry or institution [2].

Digital transformation was adopted at an early stage in construction practices, but it is also streamlining construction processes to match customers' demands and preferences in the current era, especially in three integral phases of the construction lifecycle: pre-construction, construction, and facility management. Various factors affect digital transformation in the construction industry; these influence the five aspects of technology, policy, infrastructure, management, and design. The main purpose of this article is to identify and clarify the critical success factors that impact digital transformation within the construction sector. A further objective is to develop a comprehensive and methodological structure, referred to as the Digital Transformation Readiness Level Framework (DTRLF), which will serve as a roadmap that can guide construction practitioners to implement strategies for moving toward digital transformation. To achieve this objective and determine the critical success factors for implementing digital transformation in the building construction industry, the paper utilizes a hybrid approach involving expert interviews, a review of the literature on digital transformation has been completed to fill a gap with the proposed framework, then a modified Delphi technique is used to obtain a consistent level of agreement from the Delphi expert from the factors attained from the literature. The critical success factors are then classified into five overarching categories. To assess the level of agreement among the specialists, a range of statistical techniques are implemented whereby mean values and intrapersonal agreement are utilized to determine the degree of consensus. Following data analysis, the study's aim is to develop a systematic and comprehensive framework to define the importance of each factor influencing readiness level for digital transformation throughout the preconstruction, construction, and facility management phases to help the clients evaluate their digital transformation adoption gaps. The next sections will talk about the literature review that has been carried out, the research methodology, the data collected and its characteristics, the results and interpretation of the data analysis, and the conclusion.

2. Literature Review

This section reviews previous studies on digital transformation applications associated with the pre-construction, construction, and facility management phases of the construction lifecycle. It outlines the applications of digital technologies and any frameworks researchers have assessed in the context of the construction industry. The literature review is divided into four parts. First, it delineates the knowledge gap this study aims to resolve, and then it sheds light on previous studies relevant to critical success factors in the pre-construction, construction, and facility management phases, respectively.

2.1. Research Contribution and Knowledge Gaps

The existing research indicates that there is currently limited understanding of the factors impacting digital transformation in the construction industry. Previous studies have focused on specific technologies and their application in this sector; however, few studies have measured the importance of each factor in enhancing digital transformation in the construction industry, underlining the need for more analysis. Additionally, the construction industry has adopted digital transformation at a slower rate than other sectors, despite its potential to significantly enhance overall performance in construction. The constraints arise from the lack of a comprehensive framework that combines the success factors that are critical for the successful execution of digital transformation within the construction industry. This study's contribution includes the development of a framework for calculating digital transformation readiness across the preconstruction, construction, and facility management phases and throughout the entire building life cycle. This section conducts an overall review of previous studies on the digital transformation applications associated with the construction industry, including the three phases mentioned above, in order to describe the applications of digital technologies and any relevant frameworks assessed in the context of this industry. The literature review is divided into three sections dealing with digital transformation in the pre-construction, construction, and facility management phases of the building life cycle, respectively. Prior studies have investigated the benefits, approaches, and obstacles that impede the adoption of digital transformation in the construction industry. However, as far as the authors are aware of the summary table of previous literature, there has been minimal attempt to provide a comprehensive global analysis of the utilization, advantages, and difficulties of digital technologies in the three main stages of preconstruction, construction, and facility management. The majority of the paper focuses on distinct technologies or specific phases. The main aim of this paper is to thoroughly analyze articles that discuss the use of digital technologies in the construction industry, with a specific focus on their demonstrated efficacy. This study contributes to the existing knowledge on the digital transformation of the construction industry by conducting a thorough review of the recent literature on the use of digital technologies in construction, as well as the policy and infrastructure factors that influence this transformation. Moreover, the paper examines the necessary infrastructure and policies to enable digital transformation during these stages. Thus, it addresses the lack of information regarding the three distinct stages (pre-construction, construction, and facility management) that are covered in articles focusing on particular technologies.

2.2. Selection of the Success Factors in Building Construction

2.2.1. Pre-Construction Phase

This section highlights the factors that impact the pre-construction phase. These factors are divided into four types: technologies, policy, design, and management.

Technology

This section introduces a range of technological factors and applications that have the potential to be utilized in the pre-construction phase. Case studies of the use of these technologies are then presented to further illustrate their significance and their potential applications in the pre-construction phase. The use of drones during the pre-construction phase helps to enhance communication between stakeholders during design, site survey, and planning [3]. Additionally, drones can enhance safety by evaluating project risks and simulating hazardous scenarios. According to [4], building information modeling (BIM) is another important technology. BIM can help optimize space layout and improve contractor selection. Moving on to the artificial intelligence (AI) revolution, AI has the potential to significantly impact pre-construction activities by analyzing data. For instance, it can distinguish appropriate candidates by considering various criteria such as past performance, expertise, experience, and cost [5]. It has recently become possible to utilize blockchain technology to oversee construction contracts and project costs [6]. These technologies smooth processes and ensure data accessibility in the pre-construction phase. When working with geometry and spatial dimensions, geographic information systems (GIS) can be utilized to analyze land development data, according to [7]. Meanwhile, virtual reality (VR) can help detect defects in 3D models, and the integration of VR technology can enhance communication, stakeholder engagement, and design visualization during the pre-construction phase [8]. Using an agent-based modeling approach, cybersecurity technology is used to identify risks, threats, and vulnerabilities in terms of processes, entities, and stakeholders [9]. The integration of these technological components into the pre-construction phase has a profound impact, improving effectiveness, cooperation, and the quality of decision-making. With the ongoing integration of technological advancements in the construction industry, the pre-construction phase will be subject to additional innovations paving the way for construction projects that are more sustainable, cost-effective, and proficiently executed.

Policy

Policy and regulation play a critical role in streamlining the implementation of technology in the construction industry. Therefore, the concept of Construction 4.0 has recently been examined in previous articles. According to [10], the objectives and aims of Construction 4.0 comprise a comprehensive strategic plan that includes the establishment of an ecosystem-compliant approach, the creation of a pilot project, the definition of capabilities, the generation of data, and the initiation of digital enterprise transformation. For example, Ref. [11] highlights the use of BIM to facilitate effective stakeholder engagement in Malaysia for Industry 4.0, and also emphasizes the importance of real-time collaboration for resource management, planning, and decision-making. Apart from this, the authors recommend technological training programs to increase awareness of the Construction 4.0 revolution and highly recommend that associations and organizations take proactive steps to attract highly skilled personnel, promote efficiency, and facilitate the intergenerational exchange of knowledge. The notion that upskilling and reskilling training sessions enhance the performance of an organization's workforce is reinforced in [12]. These sessions provide a foundation for continuous learning, background knowledge on Industry 4.0-related skills, and a future-ready workforce. Regarding the availability of technical specifications and standards, the study by [13] conclusively demonstrates that the lack of policies and standards in South Africa hinders the implementation of Construction 4.0 technologies. Digital transformation underscores the significance of policies and standards in furnishing a trajectory toward accurate implementation.

Design

According to [14], the design stage relies heavily on the utilization of technology and the use of new design tools, resulting in a substantial improvement in productivity. The incorporation of BIM technology in the design phase is notable, for example, in the sustainable development of China's construction industry. According to [15], during the design stage, the incorporation of technology can serve as a crucial tool to improve stakeholder engagement and mitigate risks. Utilizing VR technologies can offer a visual representation of a structure, giving an idea of its appearance.

Management

In this stage, digital transformation is crucial for improving decision-making through the use of augmented reality (AR) technology. This technology increases the pre-construction planning process by providing up-to-date information about underground utilities and thereby improving decision-making for project teams, as mentioned in [16]. Several organizations have implemented initiatives to leverage technology for management purposes, particularly during the initial stages of a project. Furthermore, Ref. [17] states that one of the digital tools being utilized is blockchain technology, which is being adopted in the tendering process alongside smart contracts. This implementation has effectively ensured the integrity of the information provided by all parties involved in the tendering process and has also enhanced project governance.

2.2.2. Construction Phase

This section highlights the factors that impact the construction phase, which are divided into three types: technologies, policy, and infrastructure.

Technology

This section concentrates on the technologies that have modernized construction site activities in terms of monitoring progress and collaboration among stakeholders and team members. In the construction phase, a variety of technologies and tools are crucial to achieving the objectives of increased productivity, on-site progress, safety, reporting, and overall good performance. Drones, for example, make a valuable contribution to the process of hazard identification by generating high-resolution aerial images and 2D and 3D maps [18]. Moreover, Internet of Things (IoT) sensors and wearable technology have been used to facilitate the continuous observation of worker safety and environmental temperature, humidity, and air quality [19]. In addition, Ref. [20] shows that robotics is utilized in modular construction, wall spraying, and excavation. Moreover, some studies have shown that 3D printing can be employed in the production of precast concrete panels, concrete walls, and mortar for walls and facades [21,22]. Interoperability in lean construction and BIM has also become a hot topic, as it improves data analysis, coordination, and communication [23]. Meanwhile, the use of AI in the construction phase enhances overall productivity and efficiency by facilitating analysis of material and property data, pattern detection, and other contributions [24]. A study on blockchain technology indicates that it has impacted confidence and transparency in the realm of construction projects [25]. There has also been tremendous usage of GIS technology for the visualization of site conditions, offering significant advantages [26]. AR/VR, on the other hand, facilitates remote collaboration, provides real-time risk information, and helps monitor progress [27]. Cybersecurity protocols can secure communication channels like message platforms and virtual private networks [28]. Finally, 3D laser scanning can capture regular on-site operations and generate virtual 3D models [29]. These technologies are core factors in improving digital transformation in the construction phase, which impacts overall performance.

Policy

To manage the proper implementation of the above-mentioned technologies in the construction phase, regulations and policies governing construction sites must be set. First, in relation to training sessions, a skills gap in the industry concerning Construction 4.0 technologies was identified by [30]. The research indicates nine determinants that influence the implementation of these technologies, including inadequate knowledge or ambiguity regarding technological advancement, uncertain employment opportunities for adept personnel, and reliance on external talent. Ref. [31] underscores the significance of resolving deficiencies in the present skill sets of project personnel and the need to acquire knowledge of emerging technologies and processes. Moreover, stakeholder engagement, as described by [32], provides a multitude of benefits, such as creating a forum for collective discussions regarding matters of public interest, promoting inclusiveness, and encouraging coordinated efforts to address shared challenges. Stakeholders significantly contribute to improving the construction process through their expertise in change management and technology. Moving on to the standardization of construction management procedures, as mentioned in a case study in Ireland [33], standardizing technology adoption in the construction industry requires technology standards to be defined, personnel to be trained, policies to be developed, performance to be monitored, and processes to be continuously refined. This standardization process can help ensure that projects are completed on schedule and within budget, as well as facilitate the effective and efficient use of technology. Standard operating procedures should outline what technology should be used for, the individuals or entities accountable for its operation, and the anticipated results. According to [10], a combination of effective methodologies, governance frameworks, and expert judgment is necessary for construction digitalization to be successful. Therefore, technologies must be aligned with proper regulations, training skill sets, specifications, and standards.

Infrastructure

This paragraph dives deeply into the concept of infrastructure as the main enabler of data transfer during construction activities. Few articles have mentioned the important role that proper connections on-site play in enabling technologies to work well and avoiding disruption. In the construction phase, infrastructure must enable the transmission of a substantial volume of data in a seamless manner, and robust measures for connection, storage, monitoring, and control are required. As demonstrated in [34], IT support plays a crucial role in enabling progress in building construction by guaranteeing the seamless exchange of information. Emphasizing the importance of firmly established infrastructure for data access and storage, Ref. [35] explains the critical stages involved in the digital transformation of buildings: data sensing, data connection, data storage, and data processing. When transmitting enormous amounts of data, sensing and connecting processes depend on sensor devices and cellular networks such as 5G. The importance of data storage thus becomes apparent; secure storage locations are required, whether on local servers or the cloud. Cloud computing also plays a crucial role in the migration of organizational data to the cloud, as discussed in [36]. Local hardware storage systems, such as server rooms and data centers, are examples of such systems. The author identified cloud computing as an essential element of the infrastructure required for the management of corporate data, especially when combined with wireless networks and the IoT. The establishment of a control center for construction work is of utmost importance for the oversight and regulation of construction. Finally, the implementation of digital technologies necessitates the use of wireless networks and low-latency, high-bandwidth connections [37]. In essence, the digital transformation of the construction industry as a whole and the digitalization of smart buildings are both fundamentally dependent on communication infrastructure.

2.2.3. Facility Management

This section highlights the factors that impact the post-construction or facility management phase. These are divided into three types: technology, policy, and infrastructure.

Technology

This section illustrates the importance of technology during the facility management phase, which directly follows the construction phase. The management of property or facilities is linked to asset management and ensures the longevity of the building as a whole. Various types of technology play critical roles in improving facility management, although some of these have yet to be implemented. The most important technology in the facility management phase, BIM, is an essential component of facility management's digital transformation. Ref. [38] collected data on extant buildings through the utilization of BIM technology, implementing it effectively to acquire data via unmanned aerial vehicle (UAV) photography, 3D laser scanning, and computer-assisted design (CAD). This functionality facilitates the incorporation of data management systems, including maintenance management systems and computer-assisted facility management systems. The integration of BIM with digital twins (DT) improves facility management operations and energy efficiency [39]. Moreover, the use of cloud-based DT enables informed decision-making by producing accurate data on physical facilities [40]. Moving on to an important part of the facility management phase, the IoT facilitates precise data acquisition and the transmission of construction resources, thereby augmenting user engagement with the built environment via intelligent digital interfaces. Radio frequency identification (RFID) technology is a crucial IoT enabler [41]. Drones aid in the execution of maintenance procedures through the acquisition of high-resolution images and videos of building components [42]. Robots find application in a multitude of facility management functions [43], encompassing facade removal, cleaning, painting, fire safety, and building inspection. AI enhances the sensing and actuation capabilities of DT technology, while blockchain enables smart contracts to be used for facility control and repair administration [44]. Ref. [45] states that GIS is utilized in facility management for environmental monitoring, planning, and safety surveillance purposes. Facility management has been transformed by AR and VR through the visualization of real-time asset monitoring in buildings [46]. Ensuring the accuracy and utility of data is of the utmost importance and requires the resolution of cybersecurity challenges [9]. In order to precisely record structural parameters, 3D laser scanning, and photogrammetry are indispensable, while a combination of UAV photogrammetry and laser scanning data can provide a comprehensive 3D representation, as mentioned in [47].

Policy

This section discusses the importance of building facility management policies and administrative regulations in the context of digital transformation, and how laws and strategies can align them with digital transformation. A lack of policies regarding the implementation of digital technologies is a potential impediment to the process of digital transformation. In Indonesia, inadequate policies on governance, services, institutions, planning, and strategy have hindered the digital transformation of the government, leading to insufficient budgetary allocations [48]. Ref. [49] recognizes reskilling and upskilling as essential components of digitalization in the construction industry, while Ref. [12] proposes a holistic shift in education, skills development, awareness, and competencies. Government intervention is needed to define the necessary skills and ensure strategic alignment between digital transformation and the workforce.

Infrastructure

This section is dedicated to the establishment of the critical infrastructure that is essential for the progression of the digital transformation of building facilities. Priority is given to those components that facilitate the connectivity, storage, and management of building data. Refs. [50,51] discuss the significance of resilient communication networks in the context of digitalization. They emphasize that the successful implementation of digital transformation within an organization is dependent upon the procurement and installation of essential computing and communication infrastructure. Research by [52] demonstrates the use of 5G technology in Singapore for the implementation of smart buildings and digitalized facility management. To function properly, digital technologies such as DT, BIM, AI, AR, VR, and the IoT require wireless networks with low latency and high bandwidth [53]. Moreover, there are infrastructural requirements for the storage and management of organizational data. Ref. [54] describes four critical stages in the process of digitalizing facilities: sensing, connecting, preserving, and processing data. They also emphasize the significance of connectivity in the context of data transfer.

Prior studies have explored the diverse benefits, approaches, and obstacles that impede the adoption of digital transformation in the construction industry. However, based on the authors' knowledge and the previous literature, there has been minimal attempt to provide a comprehensive global analysis of the utilization, advantages, and obstacles of digital technologies in the three main phases of preconstruction, construction, and facility management. The majority of the papers focus on distinct technologies or specific phases. The main aim of this paper is to create a systematic and thorough framework for assessing the significance of various factors that impact the readiness level for digital transformation across the preconstruction, construction, and facility management phases. This framework will assist clients in evaluating the gaps in their adoption of digital transformation. This study contributes to the existing knowledge by conducting a thorough quantitative analysis of the identified factors from the literature on the use of digital technologies in the construction industry. Moreover, the paper examines the necessary factor groups to facilitate digital transformation throughout these phases. Thus, it addresses the lack of information regarding the three distinct phases (pre-construction, construction, and facility management) that are covered in articles focusing on technologies.

3. Research and Methods

Figure 1 presents the research method used in this study, which is as follows. First, the digital transformation factors in construction were identified from the literature review in terms of pre-construction, construction, and facility management phases. The importance of these factors in building construction was then reviewed, and the role of each factor in terms of improving digital transformation in the pre-construction, construction, and facility management phases, as well as the relevant interpretations, were reviewed. The initial phase of the study centered on pinpointing the factors critical for the success of digital transformation in the construction industry in relation to the three main phases of preconstruction, construction, and facility management. This was achieved by conducting a systematic literature review. Searching the literature allowed us to gather more insights into best practices in digital transformation within the construction industry. Following this, semi-structured interviews were conducted with four construction executives to validate and categorize the identified factors.

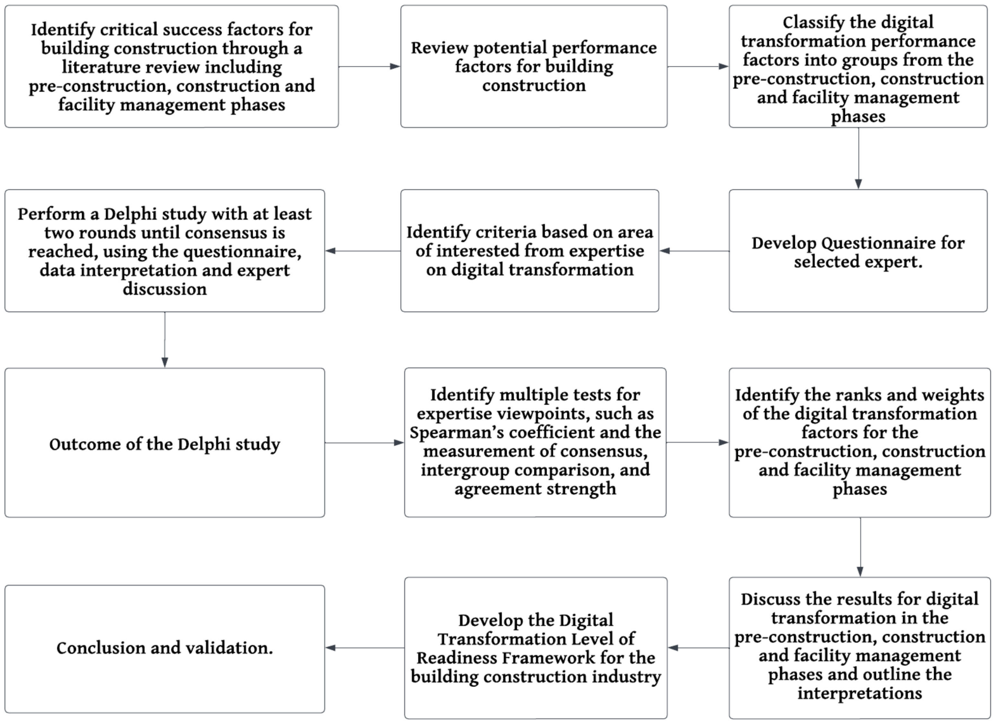

Figure 1. Methodological process used in this study.

The next phase of the research involved methodically gathering data and performing statistical analysis to ascertain the importance of different variables. This stage encompassed the establishment of expert selection criteria, the implementation of two rounds of Delphi research, and the subsequent analysis of the collected data. Each participant evaluated the importance of each factor; after the first round of rating was complete, the second round was initiated, and tests for consistency and normality were conducted to determine when to stop the rounds. The collected information was subsequently assessed for consensus, reliability, and normality.

In the concluding phase of this research, a construction industry-specific Digital Transformation Level of Readiness Framework (DTLRF) was developed and verified. The construction experts' identification of the most important digitalization readiness factors served as the foundation for this framework. Conclusions were then drawn, after which the implications of the research were examined.

3.1. Identification of Digital Transformation Performance Factors

The identification of factors that explain and exemplify the significance of digital transformation readiness in the context of building construction projects was accomplished through an examination of the existing scholarly literature. The research methodology employed for the identification of digital transformation factors followed a systematic approach involving thorough searching and screening procedures. The research methodology utilized a filtering process and targeted keywords to conduct a comprehensive literature review, ensuring the inclusion of all appropriate factors relating to digitalization within the construction sector. In the first phase, a systematic literature search was conducted using Scopus, Google Scholar, Web of Science, and American Society of Civil Engineers (ASCE) literature databases. The keywords used were "pre-construction", "construction", "facility management", "digital transformation", "technology applications", "policy", "training", "infrastructure", "construction 4.0", "digitalized construction", "digital construction", and "smart buildings".

Following this, a comprehensive analysis was conducted on a total of 234 relevant articles, which were carefully selected based on the similarity between their titles, abstracts, keywords, and the overarching subject of digital transformation in the construction industry sector. From these articles, an initial set of 59 key success factors, methods, and activities was obtained. To validate the success factors identified through this analysis and to prepare for the subsequent Delphi rounds, interviews were conducted with four experienced professionals in the field of construction; these interviews followed a semi-structured format. The main purpose of these interviews was to determine and incorporate any additional critical success factors relevant to digital transformation in the construction industry, while also eliminating any duplicates and improving the terminology used in the research. The purpose of this collaborative effort was to improve the quality and overall coherence of the list of factors to be included in the Phase 2 questionnaire. The interview process drastically reduced the number of critical success factors, making the reduced set of factors more suitable for assessment in the subsequent Delphi rounds. The interviewees and the Delphi procedure were chosen in strict adherence to the criteria outlined in Section 4.1.

3.2. Delphi Method and Panelist Selection Criteria

Phase 2 of our study included the accumulation and analysis of data, as well as the formulation of a clear procedure for selecting experts and planning the Delphi method rounds. The Delphi method was chosen for this study because it was appropriate for conducting an in-depth analysis of new insights, evaluating the relative importance of various contributing factors and groups and validating the development of the proposed digital transformation model for the construction industry.

Initially, a comprehensive questionnaire was distributed to a panel of 13 experts (Table 1), who were tasked with evaluating an initial list of relevant factors and encouraged to suggest any additional factors they deemed significant. These suggestions were then subjected to validation through a comprehensive review of existing literature. Subsequently, a second round was conducted to revise the questionnaire by integrating feedback and comments from the first round and incorporating the newly identified critical success factors.

Table 1. Characteristics of Delphi panelists.

Number	Organization Type	Current Role	Education Level	Years of Experience
1	Contractor	General Manager	Master's degree	21
2	Contractor	Engineering Manager	Bachelor's degree	20
3	Contractor	Project Manager	Bachelor's degree and PMP-certified	25
4	Consultant	Project Director	Master's degree	19
5	Consultant	Design Specialist	Bachelor's degree	15
6	Consultant	Engineering Services Specialist	Master's degree	15
7	Consultant	Senior Quality Manager	Bachelor's degree and PMP-certified	20
8	Consultant	BIM and Digitalization Specialist	Ph.D.	15
9	Client	Project Manager	Bachelor's degree and PMP-certified	20
10	Client	FM Manager	Master's degree	24
11	Client	Engineering Manager	Bachelor's degree and PMP-certified	25
12	Client	Quality Manager	Bachelor's degree	22
13	Client	Digitalization Specialist	Master's degree	18

Note: Ph.D.—Doctor of Philosophy; PMP—Project Management Professional.

3.3. Administration of the Questionnaire

An initial version of the Delphi questionnaire for the 59 factors driving digital transformation in the construction industry was prepared based on a review of the literature and feedback from four construction professionals.

There were two sections to this questionnaire. The first section contained a brief description of the questionnaire and collected demographic data from the participants. In the second section, the participants were asked to rank the 59 factors according to their importance for the performance of the construction industry and its level of readiness for digital transformation. A five-point rating system was used: 1 indicated unimportance, 2 indicated slight importance, 3 indicated moderate importance, 4 represented high importance, and 5 represented extreme importance.

The questionnaire was distributed to thirteen construction specialists, all of whom responded, giving a response rate of 100%. Following the initial Delphi round, the list of factors was subsequently revised to include 11 additional suggestions from the respondents, bringing the total number of factors to 70. A table detailing all factors is provided in the following section.

3.4. Criteria and Steps for the Delphi Process

The digital transformation performance factors were rigorously assessed and ranked through a meticulous two-round Delphi process that was carefully conducted to ascertain the factors' respective influence on the construction process. The methodology employed for this Delphi study consisted of the following principal steps:

1. Expert Selection Criteria and Identification: The procedure began with the establishment of stringent criteria for selecting design, construction, and facility management experts. Due to the emphasis placed on their knowledge and experience, qualified experts were identified for the Delphi study.
2. Expert Invitation and Minimum Expert Threshold: Following the identification of experts, formal invitations were sent, along with a detailed cover letter describing the objectives of the study. The study also determined the minimum number of experts necessary for a reliable and representative Delphi panel.
3. Preparation and Pilot Testing of the Questionnaire: An initial questionnaire was crafted with care to collect expert opinions on digital transformation performance factors. This questionnaire was pilot-tested to improve its structure and clarity, thereby ensuring the validity and dependability of the collected data.
4. After selecting experts and informing them of the study's objectives, a ranking and justification questionnaire was administered. The experts ranked the digital transformation factors and provided explanations for their rankings to facilitate a thorough comprehension of their assessments.
5. Data Collection and Evaluation: The responses from the experts were compiled and evaluated systematically, with the experts' evaluations and justifications being reviewed to identify trends, patterns, and areas of agreement or disagreement.
6. Calculation of Mean Estimates and Standard Deviation: The median and mean rating values were calculated for each digital transformation performance factor. Standard deviations were also calculated to reveal the extent of agreement or disagreement among the experts.
7. Estimation of Variances for Revision: In cases of significant disagreement or variation, experts were informed of variance. They could then review their own and their peers' responses, weigh justifications, and adjust their rankings as necessary. The objective of this iterative procedure was to reach consensus through multiple rounds.
8. Repetition of Steps 5–7 until Consensus is Reached: Steps 5 through 7 were repeated iteratively until the experts reached an acceptable level of consensus or predetermined criteria for consensus, such as stability in rankings or specific standard deviation levels indicating agreement.
9. Once consensus had been reached or predetermined criteria had been met, conclusive results, rankings of digital transformation performance factors, and significant conclusions from the Delphi process were generated. These findings provided the foundation for the conclusions and recommendations of this study.

4. Data Collection and Characteristics

4.1. Demographic Data

Ref. [55] defines the Delphi method as a social research methodology that solicits trustworthy feedback from a panel of experts. The Delphi method is a popular tool for gathering up-to-date practical ideas and is applied in social science, education, and construction management research [56,57]. This methodology is crucial in situations where objective data are not available, scientific evidence is inadequate, or testing would be impractical or unethical. Moreover, Ref. [58] tested 90 papers in combination with the Delphi statistical tool in construction management, whereby the output illustrated the feasibility of using those techniques.

The Delphi process incorporates the use of standardized polls and subsequent statistical analysis to extract important information from expert responses; this is a vital feature of the Delphi approach [59,60]. Ref. [57] showed that the Delphi method is a good way to manage contract administration and the performance of construction projects. They also used statistical tools like standard deviation to mean ratio (SDMR) to analyze the results of the two rounds. Researchers in construction and engineering management (CEM) tend to use traditional methods, but sometimes those methods cannot measure the importance of some factors in certain areas of construction. Thus, Delphi has been heavily used in CEM as a means of studying the factors that impact complex processes based on information provided by specific panelists and rounds of determination [59] over time.

Recently, Ref. [61] studied the factors impacting the performance of facility management on campuses by using the Delphi method with 13 experts. Another study evaluating the impact of factors affecting change order management in project management also used the Delphi method with 13 experts [62]. A prominent feature of Delphi studies is the lack of a broadly accepted consensus regarding the minimum number of panelists necessary to carry out a comprehensive study. The primary reason for the variance in panel size is the inherent adaptability of the Delphi technique, which allows the method to be customized to align with each study's unique objectives and difficulties. The lack of a definitive consensus on this issue in the literature was emphasized by [63]. The variation in the sizes of expert panels becomes evident upon closer examination of previous research. In the study by [64], it was determined that a panel consisting of 10 to 15 experts could be deemed adequate, given that their backgrounds and experience were substantially similar. In contrast, Ref. [59] advocated for a more limited selection of 8 to 12 experts for a Delphi investigation. The study by [65] showcased a successful implementation with the participation of 14 experts across three iterative cycles. In contrast, the study by [66] included a larger panel consisting of 20 experts, although the technique used was a single-round Delphi method. Moreover, the study by [67] showed that significant and meaningful insights can be derived by engaging a limited number (seven) of experts in a series of three rounds. The extensive variability of panel sizes highlights the flexibility and adaptability of the Delphi approach, which can be customized to align with the distinct aims of individual studies. This ensures that expert perspectives are efficiently utilized, irrespective of the panel size selected by the researchers. According to the thorough examination of 90 scholarly articles by [58], the prevailing trend in the current body of literature on Delphi studies involves the inclusion of expert panels comprising 8 to 20 professionals. The impact of participants' degree of competence on the effectiveness and reliability of a Delphi study was highlighted by [68]. This discovery is consistent with the findings reported by [57].

According to [68], the success of a Delphi study is largely determined by the panelists involved in the study and their level of agreement. Since this research depended on highly skilled experts in different phases of construction (preconstruction, construction, and facility management) and required the participation of experts in digital transformation in the construction industry, the participants had to fit the following inclusion criteria: (1) possession of either a Bachelor of Science (B.Sc.) degree in civil engineering and at least 15 years of experience in the industry, or a postgraduate degree and at least 10 years of experience; (2) an interest in industrial applications for digital technologies and the digitalization of construction.

4.2. Normality Test (Kruskal–Wallis Test)

The first test to be conducted on the data set was a normality test. Normality tests determine whether or not data adhere to a normal distribution. Ref. [69] shows that non-parametric statistical methods are appropriate for studies with fewer than 30 participants and non-normally distributed data. Moreover, if the correlation coefficient is close to 1, the data are considered normal. If the value is lower than the significance level, the null hypothesis is rejected. If the calculated *p*-value is lower than the chosen significance level ($\alpha = 0.05$), this suggests that the observed differences between the data and the expected normal values are statistically significant, or in other words, they significantly deviate from a normal distribution and are thus unlikely to have occurred by random chance alone. As a result, the null hypothesis (that the data are normally distributed) can be rejected. All the factors in the groups had *p*-values lower than 0.05, and this supported the performance of the next parametric test to ensure reliability and consistency among the panelists.

4.3. Reliability Test for the Delphi Questionnaire (Cronbach's Alpha Test)

Statistical reliability testing evaluates the consistency of measurements. Cronbach's alpha coefficient is applied to determine the dependability of data collected through questionnaires, particularly those involving Likert scales. Cronbach's alpha values range from 0 to 1, with values closer to 1 indicating greater internal consistency. Ref. [70] provides interpretation guidelines for Cronbach's alpha: 0.90 indicates very high reliability, 0.80–0.90 high reliability, 0.70–0.79 reliability, 0.60–0.69 minimal reliability, and 0.60 unacceptable reliability. Reliability testing of the panelists' responses showed high reliability and consistency with values are around 0.9. All values were calculated using IBM SPSS Statistics and were around 0.885 for pre-construction, 0.886 for construction, and 0.958 for facility management, as shown in Tables 2–4. The data were thus considered consistent and reliable enough to allow further analysis to be conducted.

Table 2. Test statistics for the Delphi study in pre-construction—second round.

Test Statistics	All	Client	Consultant	Contractor
Number of experts (N)	13	5	5	3
Cronbach's alpha (alph)	0.885	0.809	0.758	0.674
Chi-square (χ^2)	158.802	40.447	88.311	30.044
Degrees of freedom (DOF)	29	29	29	29
Spearman (*r*)	0.91	0.97	0.95	0.98

Table 3. Test statistics for the Delphi study for construction—second round.

Test Statistics	All	Client	Consultant	Contractor
Number of experts (N)	13	5	5	3
Cronbach's alpha (alph)	0.886	0.669	0.792	0.475
Chi-square (χ^2)	270	104.367	114.377	51.556
Degrees of freedom (DOF)	19	19	19	19
Spearman (*r*)	0.89	0.96	0.94	0.98

Table 4. Test statistics for the Delphi study for facility management—second round.

Test Statistics	All	Client	Consultant	Contractor
Number of experts (N)	13	5	5	3
Cronbach alpha (alph)	0.958	0.648	0.874	0.6
Chi-square (χ^2)	271.167	101.59	119.211	50.366
Degrees of freedom (DOF)	19	19	19	19
Spearman (*r*)	0.86	0.94	0.97	0.91

4.4. Data Analysis

To determine when to end the Delphi rounds, a non-parametric test must be run on non-parametric data, contingent upon the results of the normality and reliability tests. The choice to end the Delphi round process was based on two techniques that were employed to accurately determine when to end the rounds: measurement of agreement (mode value) and inter-group comparison (Spearman's rank correlation coefficient). This provided evidence of the opinions of the panelists and the degree of variation in each panelist's viewpoint between the two rounds for each component. The mean response's mode value, score, and standard deviation were determined by the Delphi survey. Chi-square test results (χ^2) showed that there was broad consensus and agreement among the panelists. An interrater agreement (IRA) study was conducted after the second round to ascertain the degree of agreement among the participants for each category and factor.

4.5. Changes in the Experts' Opinions: A Quantitative Analysis

4.5.1. Spearman's Coefficient

The inter-group correlation comparison was determined using Spearman's rank correlation coefficient (r), which was obtained after the questionnaire responses and opinions had been gathered. According to [69], this test is important because it can be used to ascertain whether participants have altered their opinions on crucial topics between rounds. Among the thirteen panelists, nine changed their opinions slightly and four kept their answers the same as in the first round. This shows that almost 30% of the respondents left their answers unchanged between rounds. This level of agreement among the panelists is considered very high since all the panelists' rankings were highly correlated with values falling between 0.86 and 0.91 for all phases, as shown in Tables 2–4.

$$\rho = 1 - \frac{6\sum_1^f d_i^2}{a(a^2-1)}$$

The variable d_i represents the discrepancy between the ranks of the panelists for the factor i in consecutive rounds. The total number of factors is denoted by f, while a represents the total number of panelists who participated in the Delphi study.

4.5.2. Measurement of Consensus

There is presently no established procedure for measuring consensus in Delphi studies [71], primarily due to the absence of a clear definition of consensus. Despite this, researchers have utilized a variety of techniques to evaluate the level of consensus among expert panelists. For instance, Ref. [72] proposed that consensus should be considered reached when experts demonstrate 80% agreement (the top two Likert scale points) and 10% disagreement. Ref. [73] suggested that there is evidence of consensus when the mode value reaches at least 3.25, whereas Ref. [57] defined it as an SDMR of less than 30%.

4.5.3. Intergroup Comparison

Intergroup comparisons are a very important method of ensuring the consistency of expert rankings. In [57,58,74], Kendall's coefficient of concordance (Wk), and chi-square (χ^2) statistical tests were used to this end.

Chi-square was used in this study to test the consensus among the group respondents and obtain further confirmation of the null hypothesis. Ref. [75] found that if the computed χ^2 value is greater than the critical value, then a consensus cannot be rejected. Therefore, the level of confidence is reached when the computed value is higher than the critical value, as indicated in Tables 5–7, which show a strong correlation between the groups.

Table 5. Factor consensus analysis—Delphi first and second rounds for the pre-construction phase.

Pre-Construction First Round					Pre-Construction Second Round				
Factors	**% MODE Score**	**Mode Value**	**Std. Dev.**	**% Std. Dev. to Mean Ratio**	**Factors**	**% Mode Score**	**Mode Value**	**Std. Dev.**	**% Std. Dev. to Mean Ratio**
P01.01	87%	5	1.8	37%	P01.01	87%	4	0.63	16%
P01.02	87%	4	1.7	42%	P01.02	87%	4	0.52	13%
P01.03	90%	5	1.8	37%	P01.03	90%	5	0.38	8%
P01.04	87%	4	1.7	43%	P01.04	87%	4	0.63	16%
P01.05	90%	5	1.8	37%	P01.05	90%	5	0.51	10%
P01.06	87%	5	1.9	38%	P01.06	87%	5	0.44	9%
P01.07	87%	5	1.9	38%	P01.07	87%	5	0.48	10%
P01.08	90%	4	1.7	42%	P01.08	90%	5	0.90	18%
P01.09	87%	5	1.9	38%	P01.09	87%	5	0.52	10%
P01.10	90%	4	1.8	45%	P01.10	90%	5	0.48	10%
P01.11	90%	4	1.5	38%	P01.11	90%	4	0.38	9%
P01.12	100%	_	0.6	_	P01.12	90%	4	0.55	14%
P01.13	100%	_	0.6	_	P01.13	87%	5	0.00	0%
P02.01	87%	5	1.9	39%	P02.01	87%	5	0.00	0%
P02.02	90%	4	1.7	42%	P02.02	90%	4	0.55	14%
P02.03	100%	_	0.6	_	P02.03	87%	5	0.00	0%
P02.04	100%	_	0.6	_	P02.04	90%	4	0.51	13%
P03.01	87%	4	1.7	42%	P03.01	87%	4	0.63	16%
P03.02	90%	4	1.7	42%	P03.02	90%	4	0.73	18%
P03.03	87%	4	1.7	43%	P03.03	87%	5	0.52	10%
P03.04	87%	5	1.9	38%	P03.04	87%	5	0.38	8%
P03.05	100%	_	0.6	_	P03.05	90%	4	0.44	11%
P03.06	100%	_	0.6	_	P03.06	87%	5	0.00	0%
P04.01	92%	5	1.9	37%	P04.01	90%	5	0.38	8%
P04.02	90%	4	1.5	38%	P04.02	90%	4	0.51	13%
P04.03	90%	4	1.5	38%	P04.03	90%	4	0.52	13%
P04.04	90%	4	1.5	38%	P04.04	90%	5	0.51	10%
P04.05	90%	4	1.5	38%	P04.05	90%	4	0.00	0%
P04.06	90%	4	1.5	37%	P04.06	90%	4	0.48	12%
P04.07	92%	4	1.6	39%	P04.07	90%	4	0.28	7%
P04.08	100%	_	0.6	_	P04.08	87%	5	0.00	0%

Note: std. dev. = standard deviation.

Table 6. Factor consensus analysis—Delphi first and second rounds for the construction phase.

Construction First Round					Construction Second Round				
Factors	**% Mode Score**	**Mode Value**	**Std. Dev.**	**% Std. Dev. to Mean Ratio**	**Factors**	**% Mode Score**	**Mode Value**	**Std. Dev.**	**% Std. Dev. to Mean Ratio**
C01.01	85%	4	0.9	45%	C01.01	95%	4	1.0	26%
C01.02	95%	4	1.0	24%	C01.02	97%	5	1.1	21%
C01.03	95%	5	1.3	26%	C01.03	92%	4	1.1	28%
C01.04	92%	4	1.3	32%	C01.04	95%	5	1.2	23%
C01.05	92%	5	1.4	28%	C01.05	97%	5	0.9	18%
C01.06	97%	5	1.1	23%	C01.06	100%	5	0.0	0%
C01.07	100%	5	0.3	6%	C01.07	97%	5	1.0	20%
C01.08	97%	5	1.0	21%	C01.08	88%	4	1.6	16%
C01.09	100%	_	_	_	C01.09	95%	4	1.0	26%
C01.10	95%	5	1.3	26%	C01.10	100%	5	0.8	16%
C01.11	100%	3	0.5	17%	C01.11	100%	4	0.7	18%
C01.12	100%	_	_	_	C01.12	100%	5	0.3	6%
C01.13	100%	_	_	_	C01.13	100%	5	0.0	0%
C02.01	100%	5	0.0	0%	C02.01	100%	5	0.7	13%
C02.02	100%	4	0.4	9%	C02.02	100%	4	0.6	14%
C02.03	100%	5	0.5	10%	C02.03	100%	5	0.0	0%
C02.04	100%	5	0.0	0%	C02.04	100%	5	0.0	0%
C03.01	100%	4	0.6	16%	C03.01	100%	4	0.7	18%
C03.02	100%	4	0.7	18%	C03.02	100%	4	0.5	13%
C03.03	100%	5	0.8	15%	C03.03	100%	5	0.8	15%

Note: std. dev. = standard deviation.

Table 7. Factor consensus analysis—Delphi first and second rounds for the facility management phase.

Facility Management First Round					Facility Management Second Round				
Factors	**% Mode Score**	**Mode Value**	**Std. Dev.**	**% Std. Dev. to Mean Ratio**	**Factors**	**% Mode Score**	**Mode Value**	**Std. Dev.**	**% Std. Dev. to Mean Ratio**
F01.01	100%	4	0.0	0%	F01.01	100%	4	0.4	9%
F01.02	100%	3	0.5	17%	F01.02	100%	4	0.4	11%
F01.03	100%	5	0.4	9%	F01.03	100%	5	0.0	0%
F01.04	100%	5	0.0	0%	F01.04	100%	5	0.0	0%
F01.05	100%	_	_	_	F01.05	92%	3	0.6	21%
F01.06	100%	3	0.7	22%	F01.06	100%	4	0.7	18%
F01.07	100%	5	0.3	6%	F01.07	100%	5	0.3	6%
F01.08	100%	5	0.6	12%	F01.08	100%	5	0.6	12%
F01.09	97%	3	0.4	14%	F01.09	100%	3	0.5	17%
F01.10	100%	4	0.6	14%	F01.10	100%	5	0.5	10%
F01.11	100%	4	0.4	10%	F01.11	100%	4	0.4	9%
F01.12	100%	4	0.5	12%	F01.12	100%	4	0.6	14%
F01.13	100%	5	0.4	9%	F01.13	100%	5	0.0	0%
F02.01	100%	5	0.0	0%	F02.01	100%	5	0.0	0%
F02.02	100%	5	0.5	10%	F02.02	100%	5	0.5	10%
F02.03	100%	4	0.4	11%	F02.03	100%	4	0.5	12%
F02.04	100%	5	0.0	0%	F02.04	100%	5	0.0	0%
F03.01	100%	4	0.5	13%	F03.01	100%	5	0.5	10%
F03.02	100%	4	0.5	13%	F03.02	100%	4	0.5	13%
F03.03	100%	5	0.5	10%	F03.03	100%	5	0.5	10%

Note: std. dev. = standard deviation.

4.5.4. Significance of the Critical Success Factors

According to [76], Likert scale intervals are categorized as follows: "not at all important" for mean values lower than 1.5, "slightly important" for scores between 1.51 and 2.5, "moderately important" for scores between 2.51 and 3.5, "very important" for scores between 3.51 and 4.5, and "extremely important" for scores exceeding 4.5. In the second phase of the study, the mean scores for the different factors were measured for each phase (see Tables 7–9). For the pre-construction phase, scores ranged from 3.69 to 5, with 53.3% of the factors considered very important and the rest extremely important. Table 8 presents the results for the construction phase, clearly showing that 65% of the factors were considered very important, and the remaining were seen as extremely important. Only one factor was considered slightly important.

Table 9 presents the data for the facility management phase, with a range of means between 2.93 and 5 showing that 60% of the factors were considered extremely important, 35% were seen as very important, and only one factor was considered moderately important. This indicates that the experts in digital transformation concluded that each of the 70 factors examined significantly contributes to the success of the construction industry's digital transformation.

4.5.5. Measurement of the Strength of Agreement

Measurement of the degree of agreement among the panelists, which is considered one of the most important parameters, showed that the experts' opinions were aligned. A useful tool for this purpose is the interrater agreement equation, which is shown below.

$$\mathrm{A_g} = 1 - \frac{2SD^2(n-1)}{n[M(H+L) - M^2 - HL]}$$

The variables used in this above formula are as follows: SD represents the standard deviation of the item, H represents the highest-ranking value (5 in this paper), and L

represents the lowest-ranking value (1 in this paper). *M* is the average value of the ranks for a single factor, whereas *n* represents the total number of panelists participating in the Delphi round.

According to [77], sample size is not an issue and IRA can be implemented regardless of sample size. An IRA value close to 1 shows high agreement. Ref. [78] defined the level of agreement, with values ranging from 0.00 to 0.30 suggesting a "lack of agreement", and values between 0.31 and 0.50 indicating "weak agreement". "Moderate agreement" falls within the range of 0.51 to 0.70, "strong agreement" lies between 0.71 and 0.90, and "very strong agreement" is represented by values ranging from 0.91 to 1.00. The results for all factors in the second round are presented in Tables 8–10. Through the application of these statistical methods, it could be deduced that a substantial level of agreement was achieved.

Table 8. Key success factor interrater agreement index, mean score, agreement level, and importance level, sorted by rankings based on the Delphi expert ratings—second round for the pre-construction phase.

Factors	Mean	Rank	StdDev	AWG1	AL	IL
P01.01	4.31	7	1.03	0.97	very strong	very important
P01.02	4.46	9	1.07	0.98	very strong	very important
P01.03	4.85	14	1.12	0.99	very strong	extremely important
P01.04	4.31	7	1.17	0.97	very strong	very important
P01.05	4.62	11	0.88	0.98	very strong	extremely important
P01.06	4.77	13	0.00	0.99	very strong	extremely important
P01.07	4.69	12	0.99	0.98	very strong	extremely important
P01.08	4.15	5	1.60	0.93	very strong	very important
P01.09	4.54	10	1.04	0.98	very strong	extremely important
P01.10	4.69	12	0.78	0.98	very strong	extremely important
P01.11	4.15	5	0.73	0.99	very strong	very important
P01.12	5.00	15	0.28	1.00	very strong	extremely important
P02.01	5.00	15	0.66	1.00	very strong	extremely important
P02.02	4.15	5	0.55	0.98	very strong	very important
P02.03	5.00	15	0.00	1.00	very strong	extremely important
P02.04	4.38	8	0.00	0.98	very strong	very important
P03.01	4.13	7	0.71	0.97	very strong	very important
P03.02	4.23	6	0.51	0.96	very strong	very important
P03.03	4.54	10	0.77	0.98	very strong	extremely important
P03.04	4.85	14	0.77	0.99	very strong	extremely important
P03.05	3.77	2	0.77	0.98	very strong	very important
P03.06	5.00	15	0.77	1.00	very strong	extremely important
P04.01	4.85	14	0.77	0.99	very strong	extremely important
P04.02	4.38	8	0.77	0.98	very strong	very important
P04.03	4.46	9	0.77	0.98	very strong	very important
P04.04	4.62	11	0.77	0.98	very strong	extremely important
P04.05	4.00	4	0.77	1.00	very strong	very important
P04.06	3.69	1	0.77	0.98	very strong	very important
P04.07	3.92	3	0.77	0.99	very strong	very important
P04.08	4.15	5	0.77	0.98	very strong	very important

Note: StdDev = standard deviation; AWG1 = interrater agreement index; very strong = very strong agreement.

Table 9. Key success factor interrater agreement index, mean score, agreement level, and importance level, sorted by rankings based on the Delphi expert ratings—second round for the construction phase.

Factors	Mean	Rank	StdDev	AWG1	AL	IL
C01.01	3.69	3	1.03	0.90	strong	very important
C01.02	3.85	5	1.07	0.90	strong	very important
C01.03	3.62	2	1.12	0.88	strong	very important
C01.04	3.77	4	1.17	0.88	strong	very important
C01.05	4.46	10	0.88	0.94	very strong	very important
C01.06	5.00	13	0.00	1.00	very strong	extremely important
C01.07	4.15	8	0.99	0.92	very strong	very important
C01.08	2.31	1	1.60	0.62	moderate agreement	slightly important
C01.09	4.08	7	1.04	0.91	very strong	very important
C01.10	4.46	10	0.78	0.95	very strong	very important
C01.11	3.77	4	0.73	0.95	very strong	very important
C01.12	4.92	12	0.28	0.99	very strong	extremely important
C01.13	5.00	13	0.00	1.00	very strong	extremely important
C02.01	4.54	11	0.66	0.97	very strong	extremely important
C02.02	4.15	8	0.55	0.98	very strong	very important
C02.03	5.00	13	0.00	1.00	very strong	extremely important
C02.04	5.00	13	0.00	1.00	very strong	extremely important
C03.01	4.00	6	0.71	0.96	very strong	very important
C03.02	4.38	9	0.51	0.98	very strong	very important
C03.03	4.38	10	0.77	0.95	very strong	very important

Note: StdDev = standard deviation; AWG1 = interrater agreement index; very strong = very strong agreement; strong = strong agreement; moderate = moderate agreement.

Table 10. Key success factor interrater agreement index, mean score, agreement level, and importance level, sorted by rankings based on the Delphi expert ratings—second round for the facility management phase.

Factors	Mean	Rank	StdDev	AWG1	AL	IL
F01.01	4.15	4	0.38	0.99	very strong	very important
F01.02	3.77	2	0.44	0.98	very strong	very important
F01.03	5.00	3	0.00	1.00	very strong	extremely important
F01.04	5.00	4	0.00	1.00	very strong	extremely important
F01.05	2.92	1	0.64	0.95	very strong	moderately important
F01.06	4.00	15	0.71	0.96	very strong	very important
F01.07	4.92	8	0.28	0.99	very strong	extremely important
F01.08	4.77	5	0.60	0.97	very strong	extremely important
F01.09	3.38	6	0.51	0.97	very strong	moderately important
F01.10	4.54	13	0.52	0.98	very strong	extremely important
F01.11	4.15	7	0.38	0.99	very strong	very important
F01.12	4.00	14	0.58	0.97	very strong	very important
F01.13	5.00	17	0.00	1.00	very strong	extremely important
F02.01	5.00	12	0.00	1.00	very strong	extremely important
F02.02	4.62	11	0.51	0.98	very strong	extremely important
F02.03	4.31	16	0.48	0.98	very strong	very important
F02.04	5.00	17	0.00	1.00	very strong	extremely important
F03.01	4.69	9	0.48	0.98	very strong	extremely important
F03.02	4.38	9	0.51	0.98	very strong	very important
F03.03	4.54	10	0.52	0.98	very strong	extremely important

Note: StdDev = standard deviation; AWG1 = interrater agreement index; very strong = very strong agreement.

The study included an all-encompassing approach that comprised a review of the literature, structured interviews, and a modified two-round Delphi process to assess and rank the 70 critical success variables related to digital transformation in the construction sector. As described in Appendix A, these factors were categorized into distinct process groups for each phase. For the pre-construction phase, group 1 focuses on the management aspect of the early stages of a project, group 2 focuses on the policy perspective, group 3 focuses on the technological aspects, and group 4 focuses on the design aspects. For the construction phase, group 1 focuses on the technologies implemented during construction, group 2 focuses on policy-making, and group 3 focuses on infrastructure. For the facility management phase, group 1 focuses on the technologies implemented in the facility management phase, group 2 focuses on policy making, and group 3 focuses on infrastructure.

5. Results and Interpretation

To assess and prioritize 70 critical success factors in the field of building projects, this study employed a comprehensive approach, which included a literature review, interviews, and a modified two-round Delphi procedure. The components discussed in Appendix A can be categorized into three phases, namely pre-construction, construction, and facility management, with respective process groups. The pre-construction groups were as follows: management, policy, technology, and design. In the construction and facility management phases, these groups were divided into three categories, namely technology, policy, and infrastructure.

As shown in Tables 7–9, following the conclusion of the two Delphi rounds several key factors were determined to be "extremely important" based on mean ratings. Notably, group 2 (policy and regulation) includes 66.6% of the critical factors, while 53.3% belong to group 1 (management); group 3 (technology implementation) includes 37.5%, group 4 (design) includes 37.5%, and lastly group 5 (infrastructure) includes 33.3%. In general, the significance of any given process group can be determined by assessing both the significance of its constituent key factors and the group's influence on the other process groups.

As shown in Figure 2 and reflected in Tables 7–9, which clearly illustrate a breakdown of the relative importance of factors during the construction project phase, around 46% of options are considered extremely important during the pre-construction phase, while the remaining options are categorized as very important. This implies a significant degree of importance across all factors. During the construction phase, approximately 65% of options are categorized as extremely important, 30% as very important, and 5% as slightly important. The extremely important option has increased to 55% on the FM pie chart, while the very important option has grown to 35%. The moderately important option has now reached 10%, thus showing the fact that most facts fall under the categories of extremely important and very important in the three phases. This is evidence demonstrating the importance of implementing digital transformation in the construction industry.

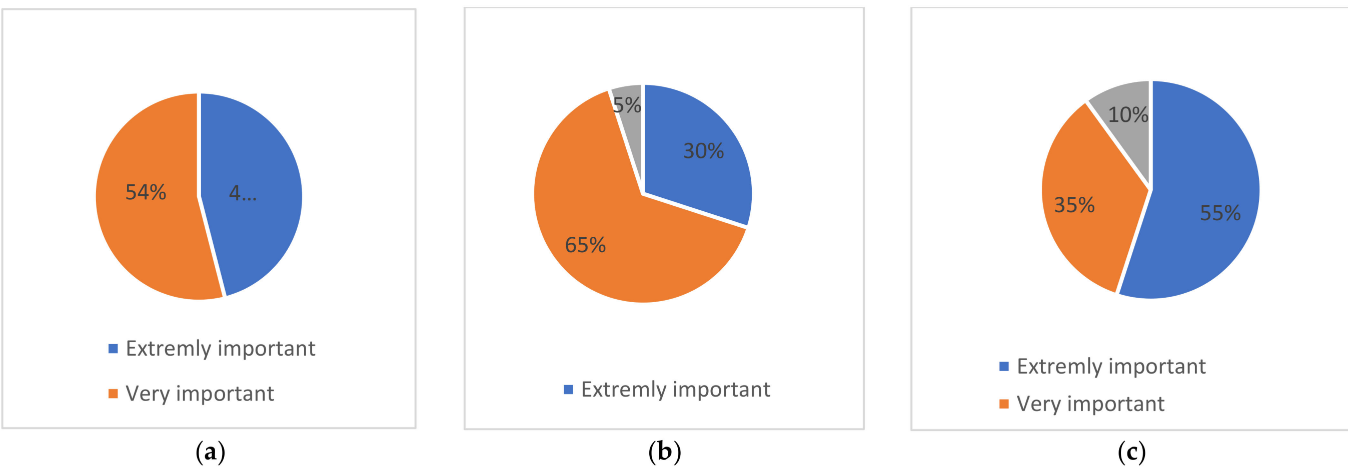

Figure 2. Factors importance level on building project phases as listed: (**a**) pre-construction management phase; (**b**) construction management phases; (**c**) facility management phase.

The policy and regulation group is crucial when it comes to the digital transformation of building projects as it establishes all the foundations required to realize the value of digital transformation. This involves having a training structure in place to upskill existing human resources and identify the proper standards to enhance synergy between efforts. Digital transformation also requires an organizational strategy to pave the way for implementation and demonstrate the commitment of the leadership toward this goal. To ensure success, leaders of construction projects should initiate an incentive program for either internal or external buy-in. Referring back to Ref. [79], both studies arrived at the importance of focusing on establishing the policies and regulations for the implementation of digital transformation in building projects. On the other hand, Ref. [80] insists that digital twin technology adoption is the main critical contributor when it comes to the digital transformation of building projects.

Management is a crucial group of factors that involves utilizing technology in the early stage of a project and properly managing the project. This includes the implementation of 4D BIM for scheduling and enhancing the design stage, as well as using AI for costing and scheduling. Digital key performance indicators and platforms can be used to enhance sponsors' engagement and keep them interested in the project. In terms of procurement, the use of big data to support project estimation and procurement is critical for the digitalization process.

Digital transformation is heavily dependent on the implementation of technology. After the required standards and pre-requirements have been established, technology can be extremely important at the early stage of pre-construction. For example, drone technology can be used for site surveys, and AI can be incorporated into planning from the early stages of a project, increasing the probability of the project's success. However, technology is relied upon even more heavily in the construction phase than in the pre-construction and facility management phases. Here, the focus is on implementing technology to enhance construction activities, for example by using robotics in building projects and IoT technologies for excavators. Effective outcomes have also been produced with the use of 5G technology, 3D modeling, and the updating of BIM while progressing in the project; 3D printing modular buildings, for example, can significantly reduce the financial and temporal cost of construction. In the facility management phase, technology also plays an essential role, for instance through the use of IoT for building security and monitoring. Similarly, drones can be used to access and inspect remote or inaccessible areas, thereby reducing the risk to humans. AI also plays a major role in facility management, for example through facial recognition technology. Implementing technology in all phases is thus critical to the success of digitalizing any building project.

Proper design is also crucial for the successful digitalization of building projects. The primary purpose of this group is to ensure the digitalization of the design phase by using technologies like 5D design to achieve optimization. This also involves utilizing virtual reality technology with detailed designs to prevent clashes and enhance stakeholder engagement. BIM can also be used to assist with spacing and layout planning. Digitally transforming this phase will increase the accuracy of the design and reduce the risk of non-conformity in the future.

The last group is infrastructure, which contributes significantly to the digital transformation of building construction because this requires data storage centers, which necessitate flows of data. Without the establishment of appropriate connection infrastructure in the construction phase, facility management digitalization cannot happen; also, from the initial phases onward, a command center is required to facilitate the control and monitoring of all this digital data. Previous research has indicated that certain aspects are more or less significant in affecting a building's digital transition. The management team must concentrate on the success criteria that have the most effect on the overall performance of digitalization.

6. The Digital Transformation Level of Readiness Framework (DTLRF) for the Building Construction Industry

The Digital Transformation Level of Readiness Framework (DTLRF) for the building construction industry is illustrated in Figure 3. The main output of this framework is the determination of the importance of digital transformation and the building construction industry's level of readiness for it. It comprises three primary levels: strategic, executive, and operational. The first of these, the operational level, refers to the routine activities in the three phases, some of which can be digitalized using the technologies mentioned above in relation to the factors influencing digital transformation. Technological factors are the core foundation of the digital transformation journey in the building life cycle. Investing in technologies might have a high initial cost but will pay off in the long run. Due to the rapid advancement of technology, organizations must think strategically about how and when to invest in technologies in the digital age. Therefore, historically, implementing technologies in pre-construction, construction, and facility management in buildings has been crucial. Each specific phase requires specific technologies that will ensure higher performance, better output, and proper resource management.

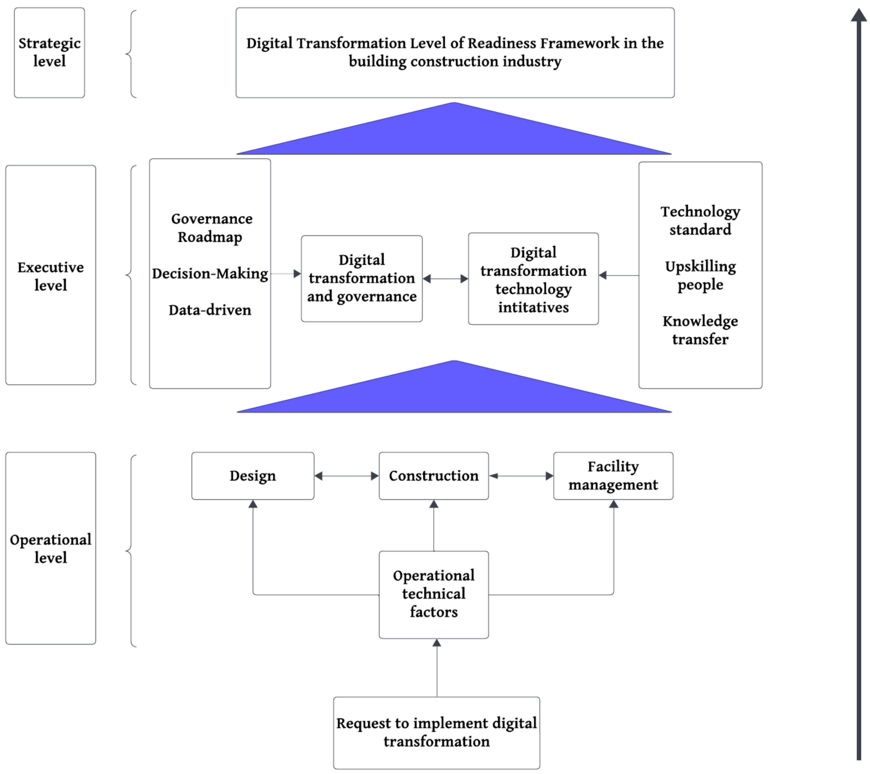

Figure 3. Digital Transformation Level of Readiness Framework (DTLRF) for the building construction industry.

However, proper infrastructure and policies are key to obtaining the best output from these technologies. This is relevant at the executive level, where middle management discusses the required policies, standards, and infrastructure with higher management to obtain a budget for the initial cost of the technology implementation. Policies can provide guidelines for clients, contractors, and consultants to ensure the appropriate use of the implemented technologies. The policy factor includes providing the right talent: this is the main initiative at this level, because without the right assets and an appropriate execution plan, the strategy will not be effectively executed. Moreover, infrastructure plays a critical role in data transfer and the exchange of knowledge. During the pre-construction, construction, and facility management phases, data are the foundation of a building project with a clear scope, and the data accumulates as the project progresses.

Therefore, a common data management system should be established to ensure proper data exchange and distribution throughout the different phases of the building life cycle. This infrastructure can be categorized as relating to connectivity, storage, or control dashboards, and is a fundamental requirement for the next phase.

The strategic level serves as a comprehensive strategic plan, integrating the principles of the digital transformation vision and aiming to drive the organization towards greater efficiency and innovation. It is critical for every independent organization within the construction sector to precisely define a strategic level. This necessitates a thorough comprehension of the present condition of the organization, its ambitions for the future, the ever-changing technological environment, and the market dynamics. At this level, developing a customized strategic plan necessitates a clear approach that corresponds with the requirements, obstacles, and objectives of the institution.

At the strategic level, guiding the organization in the right direction is of the utmost importance, and requires critical decision-making regarding the adoption of technology, the allocation of resources, and the management of organizational change. Proactive leadership is essential for the identification of potential obstacles and the development of strategies to overcome them. Furthermore, fostering a corporate environment that promotes innovation and flexibility should be prioritized, as the effectiveness of digital transformation relies on not only technological progress but also on the contributions of individuals.

The strategic planning of digital transformation within the construction sector functions as a guiding light, offering a unique and intentional trajectory. This level provides a thorough explanation of both the "what" and "how" of digital transformation, serving as an all-encompassing manual for navigating the complex path toward an organization that is technologically advanced and prepared for the future.

7. Conclusions and Future Work

In summary, the construction industry is experiencing a significant transformation due to the swift incorporation of digital technology, which is a dynamic force. Construction industry leaders are now acknowledging the immense capabilities of digital tools, which are changing the sector's historical reliance on labor-intensive and conventional methods. Utilizing the Delphi technique, this study has identified and classified 70 critical factors that exert an influence on the digital transformation of the construction industry in the domains of management, design, technology, policy, and infrastructure. These factors are here scrutinized across the entirety of the project lifecycle, from preconstruction to facility management, yielding valuable insights. The adoption of digital transformation has brought about a substantial paradigm shift in all aspects of the construction sector. Along with strict rules and policies, using technology strategically during the pre-construction phase can help define the project's scope and costs more accurately, speed up the decision-making process, make the design more solid overall, and allow for full system diagnostics. Moreover, during the construction phase, the implementation of advanced technologies can significantly reduce the time required for project preparation, facilitate efficient collaboration among stakeholders, and expedite operations. Furthermore, the integration of suitable technologies, supported by a resilient infrastructure, has the potential to significantly improve the processes of handing over projects, enhance asset management, and employ better O&M methodologies. Thus, digital transformation contributes positively to the construction industry. In addition, our proposed DTRLF (Digital Transformation Level of Readiness Framework) provides a strategic manual for diverse stakeholders, enabling them to effectively navigate and wholeheartedly adopt digital transformation in their specific fields. The output of the framework enables organizations, contractors, facility management firms, and consultants to effectively assess and prioritize digital transformation initiatives. Construction firms can subsequently develop smart strategies with the objective of improving their preparedness for the adoption of digital transformation. Potential strategies could involve placing considerable importance on the distribution of knowledge during the technology implementation phase, providing stringent policy and technical standards, and building the necessary infrastructure to facilitate the digital transformation endeavor. As the future moves so fast toward digital transformation, the future work that might be interesting to this research is to deep dive into a similar approach to infrastructure projects, as this study focuses only on the vertical project rather than the horizontal project and compares the vertical and horizontal projects. This will enrich the construction of digitalization content and give insights into where the organization is standing in terms of digital transformation. The proposed framework would allow researchers and construction professionals to make an evaluation model, like the structural equation model (SEM) or the analytical hierarchy process (AHP), to measure and rate how ready an organization is for digital transformation. This model could be used for the pre-construction, construction, and facility management phases. In order to assist facility management companies, clients, organizations, contractors, and designers in understanding the implementation of digital transformation within their respective domains and supporting decision-makers in establishing action to adapt related technologies in their respective project phases, this research led to the development of the Digital Transformation Level of Readiness Framework (DTRLF). This study makes a valuable contribution to the overall comprehension of the complex factors that drive digital innovation within the construction sector and thus promotes flexibility and improved operational outcomes.

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Appendix A

Table A1. Pre-construction successful factors.

Code	Groups and Factors	References
P01	Management	
P01.01	Implementation of AI on selection of contractors (e.g., bidder selection during tendering stage)	[5,81]
P01.02	Availability of Cloud computing to store previous past projects data (e.g., referencing on past projects data which is stored on cloud)	[82,83]
P01.03	Providing a digital cost control by using AI technology (based on cost Data base for indirect costs in pre-construction stage)	[25,84]
P01.04	Utilization of key performance indicators digital platform for pre-construction for project sponsors (e.g., KPI indicator of pre-project process, avoiding financial risk in project sponsors)	[85,86]
P01.05	Availability of digitalized estimation process for major project items (e.g., enhance cooperative and autonomous stakeholders)	[87,88]
P01.06	The availability of 4D BIM modelling for scheduling accuracy (e.g., using BIM on creating accurate schedule based on design solution)	[89,90]
P01.07	Implementation of big data and analytics for labor productivity	[91–93]
P01.08	Utilization of BIM modeling for stakeholder management (e.g., team collaboration, enhance project planning, design, and clash detection)	[94–97]

Table A1. *Cont.*

Code	Groups and Factors	References
P01.09	Availability of big data for procurement process	[98,99]
P01.10	Utilization of real-time 3D modeling for customer review	[100]
P01.11	Availability of cloud computing for tracking transmittals on pre-construction stage	[50,101]
P01.12	Utilization of cyber-security for information management at pre-construction stage (e.g., data sharing, data security irascibilities, construction cost, and contract)	[102,103]
P02	Policy	
P02.01	Regulatory incentive to use digitalized technologies in pre-construction stage	[104,105]
P02.02	The availability of LCA tools integrated with BIM model for achievement of sustainable development goals	[106–108]
P02.03	Upskilling the preconstruction team for digitalization processes	[109,110]
P02.04	The availability of digitalization standards and regulation for pre-construction management	[11,111,112]
P03	Technology	
P03.01	Using machine learning during preconstruction	[108,113]
P03.02	Implementation for 3D mapping for BIM modeling	[114,115]
P03.03	Using blockchain technology with the organization's cloud system	[116–118]
P03.04	Utilization of drones for site surveying	[119,120]
P03.05	The availability of robotics on site preparation (e.g., material mapping and localization)	[121,122]
P03.06	Utilization of GIS for site selection (e.g., land development, selecting soil investigation for proper location)	[7,123]
P04	Design	
P04.01	Using BIM modeling for the spacing layout	[4]
P04.02	Implementation of 5D for detailed engineering optimization	[124]
P04.03	Using big data and analytics for design optimization	[125,126]
P04.04	Using drones for site localization	[127]
P04.05	Utilizing digital twins on project design	[19,103,128]
P04.06	Implementation of AI to capture and assess during preconstruction (e.g., decision-making, price, experience past project performance for contractor)	[5,82]
P04.07	Integration of virtual reality with design (e.g., enhance efficiency for planning and project design)	[8]
P04.08	Utilization of laser scanning during design stage (e.g., as-built drawing, clash checks for MEP, electrical work, and improve quality control)	[129–131]

Table A2. Construction management successful factors.

Code	Groups and Factors	References
C01	Technology	
C01.01	Utilization of data management and integration during construction (e.g., stakeholder and supervision team to update data in real-time, and document traceability such as storing material testing, products, and document approvals)	[101,132,133]

Table A2. *Cont.*

Code	Groups and Factors	References
C01.02	Utilization of drones during construction (e.g., aerial map, topographic measurement, site safety, and communication, project cost, construction sustainability, and site monitoring)	[18,134–138]
C01.03	Utilization of digital twins during construction (e.g., workforce safety and risk assessment)	[19,103,128,139–142]
C01.04	Utilization of IOT (Internet of Things) during construction (e.g., sensors, wearables, and real-time site map (danger zone))	[20,143,144]
C01.05	Utilization of 3D printing during construction (e.g., prefabricated structure in-site assembly, 3D printing concrete, mortar for wall, façade, and transport construction)	[22,23,145–149]
C01.06	Using off-site or on-site robotics during construction (e.g., modular construction, wall spray, precast internal and external wall, structure elements, robotics excavation process, construction materials inspection, safety worker, and robotics bricklaying)	[21,149–156]
C01.07	Utilization of BIM during construction (e.g., 3D printing models, digital fabrication of building, and lean construction)	[24,157–164]
C01.08	Utilization of AI (artificial intelligence) during construction (e.g., fuzzy logic (material selection), deep learning, machine learning and automation, smart-helmet (over-heat temperature and installation equipment for worker safety), and better communication in transporting material on site between trucks and excavator (earthwork), big data analysis)	[97,165–169]
C01.09	Utilization of blockchain in construction (e.g., progress payment through time deliverables)	[170–172]
C01.10	Utilization of GIS (geographic information system) in construction (e.g., change in soil resources, soil depth, and strength for land development)	[7,27,173]
C01.11	Utilization of augmented and virtual reality in construction (e.g., collaborate with teams, smart devices, progress capture, training construction workers, and enhance safety)	[174,175]
C01.12	Utilization of cybersecurity in construction (e.g., security monitor and data accessibility)	[9,29,176]
C01.13	Utilization of laser scanning in construction	[47]
C02	Policy	
C02.01	Implementation of technology standard procedure in construction	[10,33]
C02.02	Engagement of stakeholders on digital transformation during construction	[11,111,112]
C02.03	Establishment of digital transformation workforce on organizational structure in the project	[177,178]
C02.04	Utilization of technology awareness session and training session for construction project team in construction	[12,31,79,179–183]
C03	Infrastructure	
C03.01	Establishment of storage and data access infrastructure to support common data environment and other information management processes	[116–118,184]
C03.02	Establishment of an effective communication network and protocol	[34,105]
C03.03	Establishment of a control center for construction works	[35–37]

Table A3. Successful facility management factors.

Code	Groups and Factors	References
F01	Technology	
F01.01	Availability of a data management system for FM (facility management) (e.g., CMMS and CAFM, etc.)	[45,185,186]
F01.02	Integration of BIM with existing FM information management systems for data accessibility	[45,187–190]
F01.03	Availability of IOT (Internet of Things) concepts in FM building components (e.g., sensors, actuators, RFID radio frequency identification and controllers smartphones, and tablets) to extract data for proper decision-making processes)	[185,191–194]
F01.04	The usage of GIS (geographical information system) database for facilities and space management	[80,118,195,196]
F01.05	Use of reality capturing tools (including 3D laser scanning, point cloud, and photogrammetry) for digital as-built/as-is model development for FM applications	[118,185,192]
F01.06	Availability of digital twins in facility management activities	[197–199]
F01.07	The adoption of UAV drones for use in building maintenance activities. (e.g., providing maintenance in difficult access locations such as roof repair and cleaning high buildings)	[118,200]
F01.08	Utilizing robotics for operation and maintenance tasks (cleaning, painting, façade replacement, fire safety, and logistics)	[43,201,202]
F01.09	Availability of security data exchange between computer maintenance management systems (e.g., cybersecurity)	[198,199,203,204]
F01.10	Implementation of XR extended reality to improve maintenance operations in FM (e.g., AR augmented reality, VR virtual reality, and mixed reality)	[46,197,205]
F01.11	The availability of digital technologies for predictive FM (e.g., artificial intelligence and machine learning for data analytics tools)	[192,206–208]
F01.12	Usage of blockchain in FM in buildings (e.g., managing service providers, ensure data integrity obtaining the required building facilities, procurement and continuing reliable and effective business operations)	[192,209]
F01.13	The availability of 3D printing for improving the facility management of buildings (e.g., replacement of damage component and creating customized complex component)	[205,210]
F02	Policy	
F02.01	Availability of organizational strategy in FM company/ operation owners for digitalization of facility management	[211–213]
F02.02	Availability of policies for implementing digital technologies in FM systems (e.g., BAS, CAFM, etc.)	[185,201,214]
F02.03	Availability of technical standards for information management systems to ensure data accessibility and retrieval	[215–217]
F02.04	Proper training for the relevant FM staff on the modern technologies to be adopted (e.g., wearable XRs (extended reality), digital twins, with ICT telecommunication protocols, AI, drones, robotics, IoT, etc.)	[45,49,182,218–220]
F03	Infrastructure	
F03.01	Availability of the proper communication network and connectivity (e.g., low latency, high network speed, no lag)	[51,221,222]
F03.02	The availability of data storage and monitoring for various building systems. (e.g., data center, server room, cloud computing, and edge computing)	[13,223,224]
F03.03	Providing a command control center for controlling building components	[50,52,193,225,226]

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