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The Impact of Digital Technology Applications on Construction Industry Project Performance

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ABSTRACT

The role of digital technology in various fields has been proven to improve industrial production efficiency, improving management efficiency, and ensuring sustainable development. The digital transformation of the industry has become an inevitable trend. At present, the application of digital technology in the construction industry is still insufficient compared with other industries. The main factors affecting the implementation of digital technology in the construction industry is that project decision-makers do not fully realize the positive impact of digital technology on project performance. Project performance is crucial to convince decision-makers to adopt advanced technology. This study systematically reviews and analyzes the literature on the impact of digital technology applications on project performance in the past decade and lists the improvements in project performance brought about by the implementation of digital technology at different stages of construction projects. The results of this study help to better understand the current level of implementation of digital technology in the entire life cycle of construction projects and the significant improvement of project performance, highlighting the important role of digital technology application in improving project performance, which is of great significance for the promotion of digital technology in the construction industry and also provides a starting point for strengthening the research on the implementation of digital technology in the future.

1. Introduction

Industry 4.0 is an initiative proposed by Germany. From 2011 to 2021, the past decade has witnessed enthusiasm for digital applications in various fields driven by Industry 4.0 technology. The term industry 4.0 has become a global term [1]. Many countries worldwide have launched corresponding strategic initiatives and introduced policies to promote the development and implementation of their major technologies, such as the Industrial Internet Alliance (United States), Industry 4.0 (Italy), Production 2030 (Sweden), and Society 5.0 (Japan). Practitioners have also conducted considerable research work [2]. "Made in China 2025" has further clarified the important

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position of digital transformation in the industry, specifically through the industrialization of the construction industry through digital transformation. As the concept of Industry 4.0 has been accepted and popularized for ten years, the European Commission announced Industry 5.0. In 2021, the fifth industrial revolution (Industry 5.0) will also occur, and the practice of the construction industry will inevitably be consistent with its values. It is worth noting that Industry 4.0 is considered technology-driven, while Industry 5.0 is particularly value-driven [1].

The application of Digital Technology (DT) has promoted digital transformation and optimized organizational structure and business processes [3]. The Construction Industry (CI) has been facing many problems in its digital transformation, including difficulties in technology integration, system instability, and data security issues, but one of the most important issues is the mismatch between stakeholders' actual expectations and value propositions and the actual effects of DT. Stakeholders now have corresponding requirements and expectations for performance brought about by the implementation of digitalization [4]. Currently, the world is in the coexistence of two industrial revolutions, and the problems raised need to be discussed and solved urgently. In the current competitive era, organizations not only require greater productivity but effectiveness as well [5]. Stakeholders hope to learn more about the practical and expected value DT applications can bring to their projects.

Earlier research focused on the investigation and analysis of specific digital application technologies, and there was less key information on improving project performance [6]. Although the application of DT in various industries has achieved certain results, its adoption in China's construction industry has not been vigorously promoted. Therefore, this study investigates and analyzes the improvement in project performance brought about by the implementation of DT at each stage of a project in China's construction industry. The results of this study will help to better understand the current status of DT implementation and the obvious improvement in project performance, which can serve as a new starting point for future research to increase the implementation of DT in the construction industry. The purpose of this study is to provide an overview of the application of DT in different construction scenarios, determine their impact on project performance through a literature review, and then use the Analytic Hierarchy Process (AHP) to analyze the research variables by inviting five industry experts to rate and assign different weights through group decision making. AHP is widely used owing to its high flexibility and wide applicability [7].

In summary, the focus of this study is: (i) to identify and clarify the impact of DT on project progress, project cost, and project quality from the existing literature; and (ii) to explore their impact weight on project performance to help decision makers make better judgments and decisions.

2. Literature Review

Engineering projects are inherently large (in value, resources, and people) and complex (multidisciplinary, distributed, and long-lived), making the effective management of time, cost, and quality extremely challenging, even for the most experienced [8]. Manually generated engineering information is outdated and may lag for a period, leading to management delays and even errors. In today's digital workplace, many sub activities and tasks are performed using digital tools, which together form a series of DT applications. In a 2022 study, 65 DT implemented in the CI were identified, from which the top ten DT of the decade were listed through statistical analysis: Building Information Modeling (BIM), Artificial Intelligence (AI), 3D printing, Machine Learning (ML), Internet of Things (IoT), Geographic Information System (GIS), Virtual Reality (VR), big data, robots, and Augmented Reality (AR) [9]. In addition, blockchain has always been a popular technology [10].

Therefore, the following research mainly focuses on the application of these ten technologies and discusses their impact on project performance.

The research noted that real-time monitoring, remote repair, and progress tracking can all be aided by the integration of smart technologies across physical and network domains. These possible uses of smart technologies can enhance management effectiveness by reducing expenses and delays while raising project quality [11]. The three knowledge domains of project time, cost, and quality management comprise the "iron triangle" as a success metric, according to the PMBOK Guide (PMI 2007). Using the theoretical framework mentioned above, this study will explore the impact of DT applications on project progress, cost, and quality from three aspects.

DT applications affect project progress. The application of DT affects project time, mainly in the overall development and control of project progress, to ensure that the project can be completed and delivered on time. Here, an application covering four aspects of project progress can be used to specifically demonstrate planning, estimating, scheduling, and controlling [12]. The previous research pointed out that monitoring project task completion or resource consumption is not sufficient to prevent or mitigate complex factors that affect project progress [8]. Therefore, DT provides richer management information, supplementing results or progress data with detailed information on the status, problems, and results of previous or ongoing activities, thereby estimating and controlling progress.

In developing countries, such as China, the development of DT and the digital economy has not only promoted China's economic growth and optimized resource allocation, but also broken-down regional market barriers and promoted the marketization of labor factors in a wider range of fields [13]. Previously, owing to the lack of real-time dynamic information, it was impossible to fully grasp the real-time status of resources and respond promptly. The integration of DT allows projects to fully grasp attributes such as time, location, quantity, sequence, and path.

Early in the implementation of DT, conflict prediction was listed as the most valuable aspect of its application. Managers selectively review conflict reports or ignore them completely, because evaluating conflicts takes a long time and has little effect. As technology develops, detection algorithms are developed, and machine learning (ML) is used to gradually automate the process [14], avoiding conflicts in advance that may have a significant impact on the future construction process.

However, by combining data-gathering tools, researchers have examined a number of approaches during the building process. (AR, photogrammetry, video measurement, laser scanning) with BIM and compared the generated 3D model with the 4D BIM model by overlapping to compare the planning model and the as-built model to achieve the purpose of construction implementation detection. It can also be applied in conjunction with photogrammetry to detect the progress of indoor projects. In addition, cluster nodes through BIM-integrated systems have been used to actively track and detect the progress of steel structural elements in construction projects [15]. The idea is to be able to use DT to access and query project status data, providing evidence for interventions and comprehensive (richer) management data, and to do so in real-time or as close to it as feasible. The previous research will help optimize the process and ensure project progress [8].

Digital technology applications affect project costs. It has been proven that many projects have cost overruns [8] were attributed to unforeseen dependencies, lack of understanding, late changes, poor communication, limited resource availability (including personnel), incomplete data, and various aspects of culture and planning. The solution is to compare the information produced and managed in the digital footprint with previously reported information and make adjustments in a timely manner.

DT are often used for asset management. The research pointed out that, in the past, information was usually contained in multiple documents (such as drawings, data sheets, equipment information folders, and maintenance record folders) [16]. To respond to possible problems (such as failures or malfunctions) or during planned maintenance, it took too much time to find and verify system information. This makes the search cumbersome and inefficient. With a digital asset management system, instant access to reliable information for decision-making can be transformed into an advantage in the quality of service provided. The utilization of DT for project visualization facilitates the identification of discrepancies between actual construction and planned specifications, which significantly impacts overall project expenses. Employing DT can reduce these discrepancies and reduce the costs associated with reworking by enhancing the construction workflow [17]. In addition, in the past, manual estimates were easily affected by uncertain factors, such as market fluctuations or different professional levels. Currently, the adoption of big data and artificial intelligence in cost management is prevalent. These technologies facilitate more accurate cost estimations by systematically categorizing and scrutinizing extensive datasets and information within construction projects. A large amount of data recorded using digital technology can improve the accuracy of budget planning and cost estimation [12].

In the previous part of this study, the application of digital technologies in resource allocation was described. Based on this, in terms of resource tracking, digital technologies demonstrate their advantages by providing logistic transparency during the construction process. DT implements this framework through material management, visualization, and real-time data management, such as the current production status throughout the building life cycle. Digital technology applications affect project quality. As construction projects become more complex, quality requirements are also increasing. Implementing DT to change construction methods and, ultimately, complete integrated digital delivery, has the potential to improve project performance.

By applying big data to project management, project quality can be transformed from extremely complex and heterogeneous data through DT analysis to valuable information. The integration of big data and predictive analytics is becoming increasingly pivotal for attaining and sustaining superior outcomes. This approach simultaneously enhances the quality of products, processes, and organizational structures. Extracting and analyzing quality data across various dimensions facilitates the effortless identification of defects and the exploration of the underlying causes of quality issues. This capability empowers project managers to predict critical aspects of quality management in a timely manner and circumvent costly post-inspection processes, thereby optimizing quality performance across the entire project lifecycle. The seamless integration of data bridges the divide between the design and construction phases, significantly diminishing the prevalence of quality-related problems.

In addition, the previous research studied the problem of the construction industry being unable to ensure quality standards, and a blockchain-based framework has been proposed for managing quality information, encompassing smart contracts, authorization sequences, and execution processes tailored for handling such data [18]. Research indicates that the amalgamation of Building Information Modelling (BIM) technology with blockchain technology can significantly enhance efficiency, quality, and security within the construction sector [19]. The impact of DT applications on project performance is summarized in Table 1

Table 1
The impact of digital technology applications on project progress, cost, and quality management

Performances	DT application
Digital technology application affects project progress	(PP1) Scheduling estimation
	(PP2) Resource allocation
	(PP3) Clash prediction
	(PP4) Real-time monitoring of construction
Digital technology applications affect project costs	(PC1) Organizational assets' data storage
	(PC2) Forecasting of project budget
	(PC3) Cash flow prediction
	(PC4) Resource tracking
Digital technology application affects project quality	(PQ1) Prediction of quality problems
	(PQ2) Decision-making in quality plan
	(PQ3) Defect identification
	(PQ4) Quality assurance tracking

3. Methodology

This study is divided into the following five steps (see Figure 1)**Fig.** . First, according to the method of literature review, the impact of the application of digital technology on project performance (project progress, project cost, and project quality) is determined through content analysis of previous studies. In the next step, the role of each DT in the application scenario under different criteria in the "solution layer" was evaluated and ranked by the group decision-making of five industry experts. The experts are all from the expert database of the China Architecture Association (who have high visibility and influence in the industry, possess senior professional certificates, and have worked for more than five years) to ensure that their opinions are of a high level of professionalism.

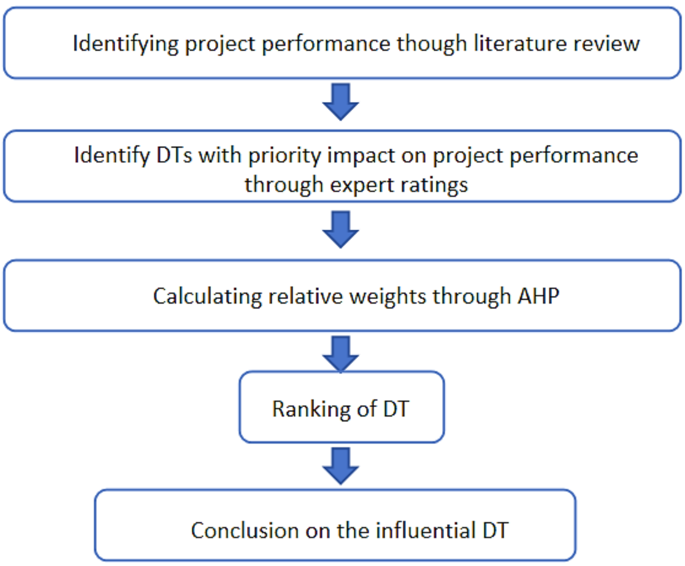

Fig. 1. Research flowchart

The scoring table adopts a nine-point Likert scale. A general measurement scale of 1-9 is issued to represent such relative importance, as shown in Table 2. This is widely used in the AHP method; its content is easy to understand, and it can express the true opinions of experts. The first part of the evaluation counted the information of the participating experts, such as years of work experience, position, and organizational role. The second part compares the effect of each DT application on project performance. Although AHP technology has a history of more than 30 years, its flexibility and robustness make it a reliable method.

Table 2
Level of the scaling

Intensity of importance	Definition
1	Completely disagree
3	Slightly disagree
5	Natural
7	Agree
9	Completely agree

4. Results

4.1 Data Analysis and Results

According to the AHP method, a hierarchy consisting of four levels, from bottom to top, was constructed. The levels of the hierarchy and AHP framework are as follows:

i. Solution level: Application of DT in construction projects.
ii. Intermediate element level: Measurement categories of DT application affecting project performance.
iii. Criteria level: Specific classification of project performance.
iv. Target level: Measurement of the most significant category of project performance improvement in DT applications, as shown in Figure 21.

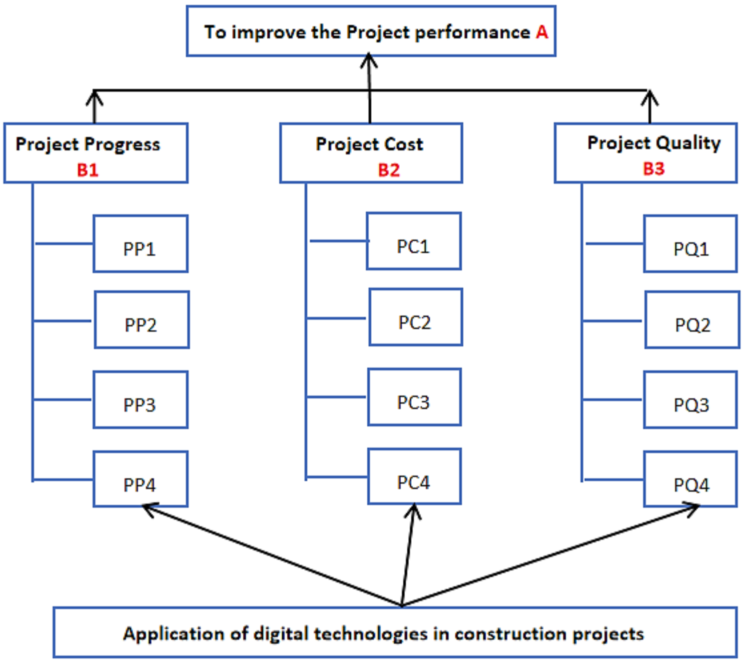

Fig. 2. Model for AHP

Establishing a judgment matrix is an important and critical part of the AHP. Indicators of the same level are compared and assigned values to form a judgment matrix composed of a judgment system. The elements of the matrix are set to a_{ij}, $a_{ij}=a_i/a_j$, a_i is the importance value of indicator B, and a_j is the importance value of indicator B. *i* and *j* represent the number of rows and columns in the judgment matrix, respectively. The judgment matrix for the same secondary indicators is listed in matrix table, as shown in Table 3. The judgment matrix composed of the aforementioned first-level indicators can be obtained as follows in section 4.1.1 and 4.1.2.

Table 3
First-level indicator judgment matrix table

$\frac{a_i}{a_j}$	B1	B2	B3
B1	1	$\frac{B_1}{B_2}$	$\frac{B_1}{B_3}$
B2	$\frac{B_2}{B_1}$	1	$\frac{B_2}{B_3}$
B3	$\frac{B_3}{B_1}$	$\frac{B_3}{B_2}$	1

4.1.1 Consistency test

Owing to the complexity of the target problem and the ambiguity and diversity of people's understanding of the problem, the consistency test is the basis for judging the objective accuracy of the results. The consistency test is one of the necessary steps in the hierarchical analysis method. The judgment matrix passed the test, which was a prerequisite for the calculated weights to be meaningful. Passing the test means that the obtained results fully explain the true weight of the indicator. The consistency indicators are shown in Eq. (1) and Eq. (2).

$$CI = \frac{\gamma_{max} - n}{n-1} \tag{1}$$

$$CR = \frac{CI}{RI} \tag{2}$$

where n is the order of the judgment matrix, and λ_{max} is the maximum eigenvalue of the judgment matrix. The RI value is related to the matrix order, and the specific values are listed in Table 4. The pairwise comparison matrix A should have acceptable consistency, which can be measured by the following consistency ratio (CR): If CR≤0.1, the consistency test passes [20].

Table 4
The average random consistency index RI value of the judgment matrix

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.141	1.45

4.1.2 Weight calculation

The summation of each column for each pairwise comparison matrix was calculated and normalized with the sum of each column, and the priority value (average value of each row) was calculated using software [21,22]. The results are shown in Figure 3. Finally, the comprehensive weight was derived from the above calculations and evaluation results. The following results were obtained, and the weight distributions of the indicators in Tables 5 to 8 are shown in Figures 4 and 5.

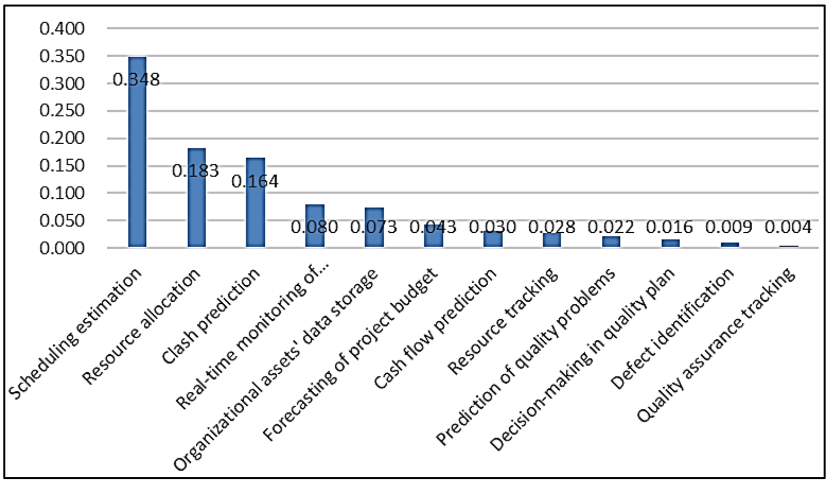

Fig. 3. Comparison of weights of indicators

Table 5
Priority values matrix a: Project performance consistency ratio (0.0904), weight of "project performance" (1.0000) and λ_{max} (3.0940)

	Progress	cost	Quality	Wi	Rank
Progress	1.000	3.000	6.000	0.635	1
cost	0.333	1.000	5.000	0.287	2
Quality	0.167	0.200	1.000	0.078	3

Table 6
Priority values matrix b: Progress consistency ratio (0.0889), weight for "project performance" (0.6348) and λ_{max} (4.2373)

	Progress	cost	Quality	Wi	Rank
Progress	1.000	3.000	6.000	0.635	1
cost	0.333	1.000	5.000	0.287	2
Quality	0.167	0.200	1.000	0.078	3

Table 7
Priority values matrix c: Cost consistency ratio (0.0850), weight for "project performance" (0.2872) and λ_{max} (4.2271)

	PC1	PC2	PC3	PC4	Wi	Rank
PC1	1.000	3.000	7.000	6.000	0.570	1
PC2	0.333	1.000	4.000	6.000	0.279	2
PC3	0.143	0.250	1.000	3.000	0.097	3
PC4	0.167	0.167	0.333	1.000	0.054	4

Table 8
Priority values matrix d: Quality consistency ratio (0.0889), weight for "project performance" (0.0780) and λ_{max} (4.2373)

	PQ1	PQ2	PQ3	PQ4	Wi	Rank
PQ1	1.000	3.000	5.000	7.000	0.549	1
PQ2	0.333	1.000	4.000	6.000	0.288	2
PQ3	0.200	0.250	1.000	4.000	0.115	3
PQ4	0.143	0.167	0.250	1.000	0.048	4

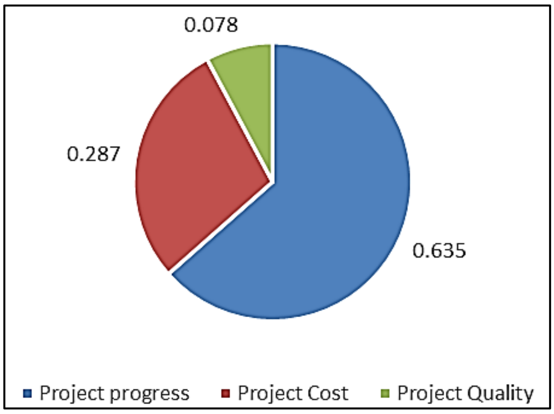

Fig. 4. The weighting diagram of the criterion layer indicators

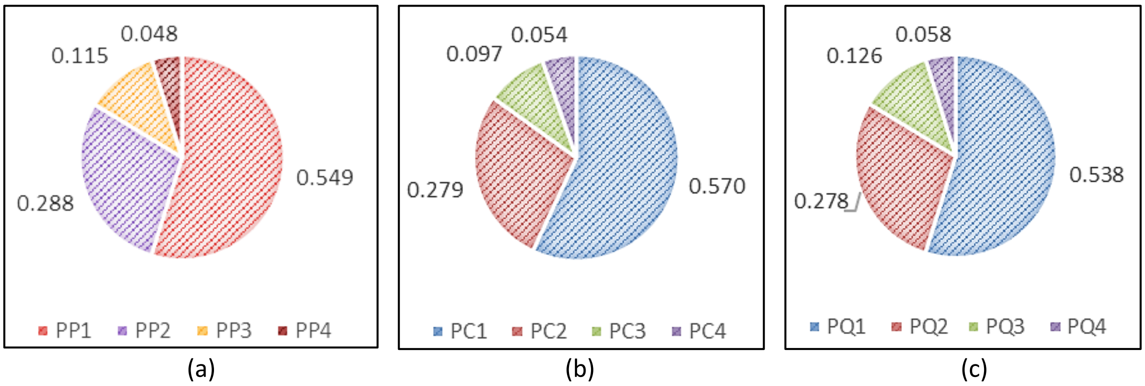

Fig. 5. Weighting diagram of scheme layer indicators (a) Weights of PP1-PP4 (b) Weights of PC1 -PC4 (c) Weights of PQ1-PQ4

4.2 Discussion

Digital technology (DT), through its various types and application scenarios, significantly enhances project management performance. According to the research results, the most significant impact of DT on project performance is on project schedule, followed by project cost, and finally, project quality. Among the primary DT application scenarios affecting project performance, the highest comprehensive weight is organizational asset data storage (PC1, weight 0.570), followed by schedule estimation (PP1, weight 0.549), and quality issue prediction (PQ1, weight 0.538). Resource allocation, project budget forecasting, and decision-making in quality planning each have a weight of less than 0.3, and thus have a relatively minor impact on project performance.

To further explore the impact of different types of DT technology on project performance, the following categories can be distinguished:

i. Physical Twin.
   (a) Data storage and management: Physical Twins collect real-time data of physical assets through sensors and IoT technology, storing this data in the cloud or on local servers. This real-time data collection and storage significantly enhances project management transparency and traceability, ensuring accurate tracking and management of project schedules.

(b) Schedule Estimation: By monitoring physical assets in real time, project managers can more accurately estimate project schedules, identify potential delay risks, and take corrective measures promptly.

ii. Virtual Twin.

(a) Quality issue prediction: Virtual Twins use simulation and modeling technology to predict and simulate potential quality issues in projects. These virtual models enable project teams to identify and address potential issues early, thereby reducing the impact of quality issues on project performance.

(b) Resource Allocation and Optimization: Virtual Twins can also optimize resource allocation and usage through simulation technology, improving resource utilization efficiency and positively impacting project cost control.

iii. Process Twin.

(a) Schedule management: Process Twins model and monitor the various stages of a project, enabling better management and optimization of project schedules, preventing scheduling conflicts, and ensuring timely project completion.

(b) Cost Estimation: Through detailed modeling of project processes, Process Twins can provide more accurate cost estimates, reducing the risk of budget overruns.

iv. Organizational Twin.

(a) Data storage and organizational asset management: Organizational Twins integrate data and resources from various departments within an enterprise, forming a unified data management platform. This integration not only improves data accessibility and utilization but also enhances overall project management coordination and efficiency.

(b) Decision Support: Organizational Twins analyze large amounts of historical and real-time data, providing scientific decision support to project managers, thereby improving overall project management effectiveness.

Through a comprehensive weight analysis, this study further evaluates the impact of DT in different application scenarios, identifying organizational asset data storage, schedule estimation, and quality issue prediction as key factors influencing project performance. The real-time monitoring and bidirectional communication capabilities provided by DT allow project plan changes to be tracked and autonomously updated promptly, thereby improving the accuracy and speed of schedule estimation.

According to stakeholder feedback, the evaluation results were generally consistent with actual situations, indicating the validity of the evaluation model established in this study. By comparing the weights of various indicators in the results, it is evident that the large amounts of data recorded by DT can improve the accuracy of budget planning and cost estimation, which is consistent with the findings of many scholars. Additionally, the weights of project quality performance-related indicators were not as significant as expected, providing a new perspective and data support for studying the performance impact of DT applications.

Scholars have confirmed the benefits of DT in projects from various perspectives. However, owing to the difficulty in quantifying some indicators, previous studies on specific changes in project performance have been limited. For further quantification, the methods used in this study can be applied for processing and analysis. This will enable stakeholders, especially decision-makers, to comprehensively understand the specific aspects of project performance enhancement through DT and accurately adopt relevant digital technologies based on their project needs.

In conclusion, this study not only enhances the understanding of DT applications but also provides valuable references for its precise application in project management. This in-depth analysis and evaluation help to better promote the application of DT in various projects, improving overall project management efficiency and effectiveness.

5. Conclusions

Many previous studies on the adoption of DT in CI have been based on the feasibility and applicability of the technology. DT can improve the productivity, efficiency, and effectiveness of work processes. However, today's decision-makers would like to understand the impact of DT on project performance from another perspective and the extent of the impact, so that they can make better decisions and judgments based on the characteristics of the project.

The digital transformation of industry has become an inevitable trend. In the era of the coexistence of Industry 4.0 and 5.0, the focus should not only be on the technology itself, but also on the more value-added performance it brings. In the construction industry, the main factor affecting DT implementation is that project decision-makers do not fully realize the positive impact of digital technology on project performance. Project performance is crucial for persuading decision-makers to adopt advanced technology. This study reviewed and analyzed the literature on the impact of DT applications on project performance in the past decade and confirmed the role of DT applications in 12 scenarios.

The AHP group decision analysis of the expert scoring results showed that DT implementation improved the overall project, project cost, project quality, and project progress performance. Among them, the impact on project progress was the most obvious, followed by the impact on project cost; however, in terms of project quality performance, performance was not as prominent as the first two categories. The results of this study help to better understand the current level of implementation of DT in the entire life cycle of construction projects and the significant improvement in project performance, highlighting the important role of DT application in improving project performance, which is of great significance for the promotion of DT in the CI and also provides a starting point for strengthening research on the implementation of DT in the future.

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