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Structural Analysis of Construction Risk Management Assessment Model Based on Digital Twins

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Abstract: Construction risk categories are complex and the most current assessment platforms tend to place focus on theoretical assessments. There is an urgent need to simulate construction risks to manage projects effectively. As such, this article proposes a digital twin construction risk assessment model (DTCRAM) based on Delphi and a case study for predicting and controlling construction risk to reduce project loss. The model has been proven to detect risks quickly and match strategies efficiently. The outcomes revealed that DTCRAM displayed better results (key risks) in predicting and controlling construction management (more than 1% probability reduction/project) while simultaneously improving management efficiency (screen out risk factors). As a result, scholars and companies can gain risk management experience by using this tool in advance.

Keywords: Digital twin, Construction risk management, Project management, Assessment model, Smart construction

INTRODUCTION

Construction risks lead to project delays, cost overruns and safety incidents (Elbashbishy et al., 2022). Most risk assessment platforms mainly focus on theoretical analysis and lack practical simulation tools that can overcome uncertainties or suggest dynamic changes in actual construction (Hu, Parhizkar and Mosleh, 2022). Digital twins (DT) reflect the construction site to improve the actual effect of construction risk management through real-time data collection and simulation (Luo et al., 2025). When faced with complex and ever-changing construction environments, DT provide accurate risk warnings and supports decision-makers in risk control and adjustments, especially when large-scale and highly complex projects are at hand (Bakhtiari et al., 2024). Many scholars have reported the potential of DT in construction risk management and achieved promising results, thus, stimulating interest and research in this technology.

One documented study (Ye et al., 2023) assessed DT simulating different support schemes and successfully avoiding potential collapse risks, including monitoring groundwater level changes in earthwork excavations. Another

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case was also noted in construction management. Since high-rise buildings experience different wind load conditions, it is crucial to optimise the construction sequence by applying the DT (Zhang et al., 2023). However, risk management still faces complex data acquisition and high implementation costs. In addition, most studies are stagnant at the theoretical and concept verification stages while lacking practical application models (Sharma et al., 2022). Delphi integrates expert opinions to eliminate subjective bias. The data of construction risk management can be more objective and offer a systematic framework (Jahanvand et al., 2023). The case study expands the scope and the practicality of practical risk management based on Delphi (De Lima and Seuring, 2023).

This present article proposes a digital twin construction risk assessment model (DTCRAM) based on Delphi and case study to address construction risk management challenges. Based on in-depth Delphi and case study, an operational digital twin model was built using real-time data and simulation technology to achieve dynamic monitoring and risk prediction in the construction, in adherence to the following specific goals:

1. To identify and evaluate key construction risk and potential risks in digital twin.
2. To extract feasible response strategies from actual digital twin cases based on the key risk.
3. To realise dynamic monitoring and risk prediction of construction sites based on DTCRAM.

RESEARCH GAPS

Conventional methods mainly rely on expert experience and static risk assessment tools, such as risk matrix and fault tree analysis (FTA) (Sharma et al., 2022). Leng et al. (2021) proposed an intelligent manufacturing system based on DT to achieve dynamic risk optimisation of the manufacturing process. Analogous, dynamic risk assessment methods are beginning to receive attention, as stipulated by building information modelling (BIM) and Internet of Things (IoT). For example, Du et al. (2021) proposed a method based on real-time data monitoring that improved the accuracy and timeliness of risk assessment. Zhao et al. (2022) pointed out the application of DT in construction process monitoring, risk management and maintenance management. Meanwhile, Eldeep, Farag and Abd El-hafez (2022) demonstrated the application of DT in construction life cycle (CLC) management in a case study and highlighted advantages in reducing costs.

However, systematic application research and practical evaluation models are lacking (Boje et al., 2020), especially in DT. The construction risk assessment model, when integrated with Delphi method and DT, achieves a comprehensive and dynamic assessment of construction risks through expert opinions and real-time data monitoring, while concurrently improving the scientific nature of decision-making. The case study demonstrates the application of DT in actual projects, highlighting efficacy in risk warning and optimised decision-making. Bhandari and Hallowell (2021) reported that Delphi can effectively reduce bias and enhance the scientific nature of decision-making through multiple rounds of anonymous questionnaires. Although DT have demonstrated potential in various fields, there are still significant deficiencies in research on its application in the construction industry (Zheng et al., 2023). Traditional construction risk management displays limitations and lags when dealing with complex and changeable construction environments.

METHODOLOGY

This article proposes the DTCRAM based on Delphi and case study to predict construction risks to reduce project losses (as shown in Figure 1). Upon identifying risk factors, response strategies and risk assessment models, an effective methodology was devised. Delphi refers to a technique that systematically identifies uncertainty factors and develops response strategies. The steps include clarifying goals, forming an expert group, designing an initial questionnaire, as well as collecting and analysing feedback. Moreover, since the analysis of risk management of DT is still in the theoretical stage, real cases were deployed in this study to expand the scenarios. By adopting this hybrid method, key risks were identified and variables were mapped in the risk assessment.

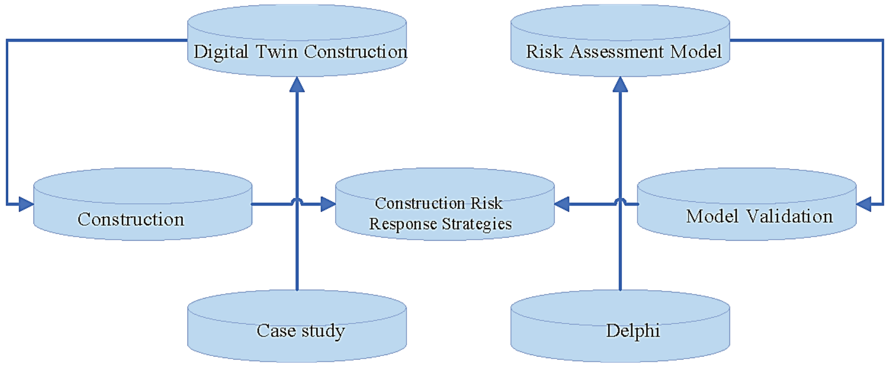

Figure 1. The DTCRAM framework

Delphi

The Delphi uses an online questionnaire based on a structured panel of experts to discuss various statements about risk management (Hamm and Su, 2021). To reach the consensus, the Delphi uses multiple rounds of surveys and multiple questionnaires. The respondents can obtain the results of each round and confirm the answers (Quirke et al., 2023). Three rounds of Delphi were used in this study that required experts (more than 5 years of experience in this area) to rank the challenges their organisations face in construction risk management and DT. Panels should not exceed 30 experts, as larger groups tend to yield limited additional insights (Barrios et al., 2021). Diversity in the expert panel should be ensured to foster different opinions. The objective of the first round is to collect different challenges faced by participants and their organisations with DT (as shown in Figure 2).

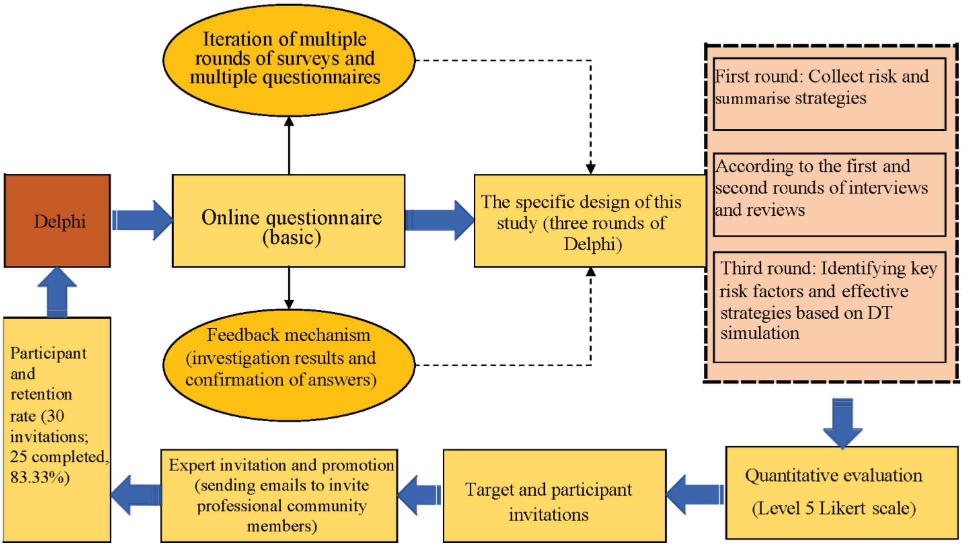

Figure 2. Construction risk and DT with Delphi

The nine-step process introduced by Kim, Lee and Lee (2020) was applied in this study. The selected panel group consisted of nine experts and odd numbers are beneficial for decision-making. All responses were aggregated anonymously from the first round and the participants were re-invited in the next round. In the second round, the panellists conducted a second round of expert interviews and the results of the first round were reviewed. In addition, a final round was designed to ask experts to identify the key risk and effective strategies. This round often reflects that the identified challenges need to be simulated by DT. For quantitative evaluation, the five-level Likert scale was used to measure the severity (1–5): "strongly agree", "agree", "general", "disagree" and "strongly disagree" (Orogun and Issa, 2022).

Given the goal of this survey is to complement the challenges documented in the literature, several experts involved in construction risk management and DT with more than 5 years of experience, such as employers and contractors, were invited for the study purpose. Professional communities related to construction risk and DT, such as the Project Management Institute (PMI) and the Digital Twin Consortium, were included as well in this study. Emails were sent to invite members of these communities to participate in the survey. An international panel of 10 professionals was initially selected. In the end, nine participants completed all three rounds of the survey (90%) (as shown in Table 1), a sample size and retention rate consistent with other Delphi studies (Harode, Thabet and Leite 2024).

Table 1. Detailed information of experts in risk management and DT

No.	Expert	Title	Work Area or Direction	Years of Experience
1	A	Professor	• Construction risk • Industry 4.0	26 (lecturer 5 years, manager 3 years, associate professor 10 years, professor 8 years)
2	B	Professor	• Digital twin and BIM • Manufacturing execution	21 (lecturer 6 years, associate professor 10 years, professor 5 years)
3	C	Associate professor	• Project management • Prefabricated project	17 (assistant 3 years, lecturer 10 years, associate professor 2 years)
4	D	Project manager	• Construction risk • Housing	16 (employee 3 years, lecturer 10 years, associate professor 2 years)
5	E	Product manager	• Digital twin • Robotic assembly in site	9 (employee 3 years, director 3 years, product manager 3 years)
6	F	Associate professor	• Information system • Industry 4.0	16 (employee 4 years, lecturer 9 years, associate professor 2 years)
7	G	Project director	• Contract and quality	11 (employee 3 years, director 3 years, product manager 3 years)
8	H	Researcher	• Digital twin and BIM	20 (lecturer 7 years, associate professor 10 years, researcher 5 years)
9	I	Senior engineer	• Construction risk	8 (employee 3 years, director 3 years, senior engineer 2 years)

Case Study

To illustrate the transformation of traditional construction risk management to DT, a five-layer structure (DT is theoretically divided into five layers [Liu et al., 2023]) was deployed in this study as a case study. The case test structure was divided into physical twins, data twins, twin models, data analysis and decision feedback (Liu et al., 2023) (as shown in Figure 3). The virtual sensors and other data acquisition devices of the physical twin were integrated into the data layer. The real-time data collected by the data twin further drove the twin model for simulation and analysis. The data analysis included in-depth risk identification, assessment and passed the results to the decision-making layer. The new data generated were fed back to the data layer to form a real-time mechanism. These feedback data were used to adjust and optimise models to ensure efficient construction process.

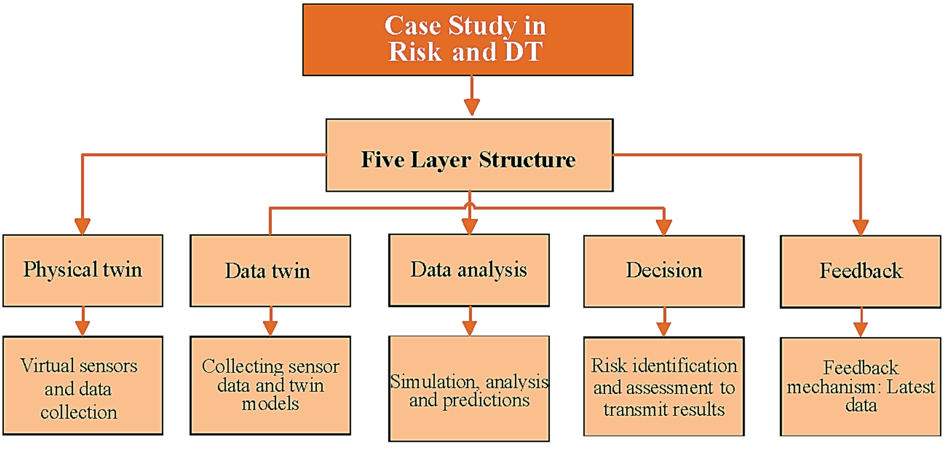

Figure 3. Construction risk and DT with case study

The physical twins deployed virtual sensors to collect data in actual cases, gathered various physical data (e.g., environmental conditions and equipment status) in real time and ensured the timeliness and accuracy of the data. By using the physical twins, all dynamic information on the construction site was captured and transmitted to the data layer. The DT is responsible for collecting and integrating real-time data transmitted by physical twins to form a data pool.

The twin model of the actual case simulated and analysed all aspects of the construction process, besides predicting potential risks and problems, especially the application of DTCRAM. The data analysis layer identified the results generated for in-depth risk assessment. The decision-making layer laid construction plans and response strategies based on the data analysis results combined with historical experience and expert opinions.

DISCUSSION

This section discusses the results of the Delphi and the case study. For Delphi, the influential factors and coping strategies of construction risks under DT were determined from the first round. Subsequently, the key influential factors gathered from the second round of research were outlined. Finally, effective strategies were outlined by experts in the third round in construction risks. Turning to the case analysis, the actual case re-analysed the construction risks and strategies, including physical twin, data twin, data analysis, decision and feedback.

Delphi

Identification of construction risks and countermeasures

The Delphi first proposed construction risks under DT with experts (as shown in Table 1). In this study, the construction risks proposed by experts matched the risks with higher frequency in the literature. For example, the description of construction risk provided by experts as "subjective identification of risks" matched the "safety risk management framework" depicted in the literature. Table 2 lists the construction risks and implementation strategies involved (matched with the literature in literature review). Therefore, DT identification of risks appeared to be more objective when compared to human subjective identification of risks. Similarly, the experts' descriptions of "forming a construction risk assessment team to identify key risks" and "DT simulation to meet risks" were related to the challenge in the literature "predicting construction risks of complex systems based on "DT expands more intelligent algorithms to carry out quality". Since all challenges proposed by the expert panel were consistent with the challenges identified in the literature, the challenges listed in Table 2 match the list of construction risks faced by the panel in three rounds.

Table 2. Consistency between construction risks and strategies and literature

Code		Risk Factors in DT	Source	Risk Strategies in DT	Source
A (Safety and quality)	A1	Worker safety	Liu et al. (2021): Safety risk management framework based on DT is presented	To predict and monitor the construction risk	Zhao et al. (2021)
	A2	Equipment safety	Liu et al. (2021): DT are introduced to building indoor safety	To simulate and predict possible failures of equipment	Ren, Wan and Deng (2022)
	A3	Construction quality	Liu et al. (2025): DT expands more intelligent algorithms to complete the project	To simulate the quality control process	Coito et al. (2022)
B (Schedule and cost)	B1	Project delay	Lee and Lee (2021): DT predicts logistics risks to minimise project schedule delay	To control the project schedule and workflow	Sacks et al. (2020)
	B2	Budget overrun	Goodwin et al. (2024): Budget and cost overrun can update the digital twin	To control the cost structure and budget allocation	Tran and Nguyen (2024)
	B3	Resource shortage	O'Dwyer et al. (2020): Construction material, shortage of labour in DT	To control the resource demand and supply of the project	O'Dwyer et al. (2020)
C (Environmental and legal)	C1	Natural disasters	Yu and He (2022): DT drives the construction of intelligent disaster	To identify the impact of natural disasters	Fan, Jiang and Mostafavi (2020)
	C2	Contract management	Pärn et al. (2024): DT within standard contracts	To identify and develop solutions in advance	Sharma et al. (2022)
	C3	Regulatory training	Moshood et al. (2024): DT included a systematic training	To identify the regulatory execution	Muhlheim et al. (2022)

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Table 2 *Continued*

Code		Risk Factors in DT	Source	Risk Strategies in DT	Source
D (Technical risk, personnel risk and management risk)	D1	Technical barriers	Tan and Aziz (2022): DT always meet technical barriers	To simulate technology and identify barriers	Perno, Hvam and Haug (2022)
	D2	Technological innovation	Tuhaise, Tah and Abanda (2023): The key technologies used in the development of DT	To simulate technology and test barriers	Michalik, Kohl and Kummert (2022)
	D3	Personnel turnover	Zhang et al. (2022): DT can avoid the risk of personnel turnover	Simulation and prediction of personnel flow	Glatt et al. (2021)
	D4	Personnel skills	Zhang et al. (2022): DT can avoid the risk of population mobility	Training and skill enhancement plan by DT	Siyan et al. (2021)
	D5	Management efficiency	Luo et al. (2025): DT applied in construction safety risk management	Management process optimisation and efficiency evaluation by DT	Yitmen et al. (2021)
	D6	Communication and coordination	Orogun and Issa (2022): DT have a deeply communication	Virtual communication platform and team collaboration by DT	Wu et al. (2022)

Correlation analysis of key risks and countermeasures

After three rounds of discussion, a consensus was reached on the nine key factors and their correlation measures for construction risk management based on DT. The nine construction risks obtained were classified as the same risks used in the literature review. Therefore, for ease of representation, NIVIO (nHoldings SA, California, USA) was applied to code the interview content. From the nine key risks identified, safety risk was related to quality risk (A), schedule risk was associated with cost risk (B), environmental risk and legal risk belonged to external risks (C), technical risk, personnel risk and management risk (D). Strengthen intelligent tracking safety training, strict quality control and design digital review, optimise construction plans and emergency plans, establish cost control and budget optimisation mechanisms, implement environmental protection and disaster prevention measures, strengthen regulatory training and contract management, conduct technical evaluation and training, improve personnel training and incentive mechanisms and improve project management level and communication and coordination.

In this set of challenges, the challenge belonging to category A, lack of comprehensive monitoring and intelligent prediction (expert 1), reached consensus with the expert group in the second round, including worker safety (A1), equipment safety (A2) and construction quality (A3). The two risks in category B, namely delay in construction period (B1), budget overrun (B2) and resource shortage (B3), reached consensus in the second round. The other two categories of risks reached consensus in the third round. This set of challenges produced three challenges belonging to category C, namely natural disasters (C1), contract management (C2) and regulatory training (C3). In addition, six challenges were observed in category D, namely technical barriers (D1), technological innovation (D2), staff turnover (D3), staff skills (D4), management efficiency (D5) and communication and coordination (D6). Table 3 shows the relevance of the challenges that the group reached consensus on, sorted by mean values. The standard deviation scores were also listed to measure the consistency of the mean values. Referring to the group assessment, the most relevant challenges were associated with the organisational category, with A3 emerging as the most relevant challenge.

Table 3. Construction risk in DT

Code		Risk Factors in DT	First Round Score	Second Round Score	Third Round Score	Mean	Standard Deviation
A (Safety and quality)	A1	Worker safety	4.11	4.33	4.56	4.33	0.18
	A2	Equipment safety	3.22	3.33	3.33	3.29	0.05
	A3	Construction quality	4.11	4.44	4.56	4.37	0.19
B (Schedule and cost)	B1	Project delay	3.00	3.33	3.67	3.33	0.27
	B2	Budget overrun	4.44	4.89	5.00	4.78	0.24
	B3	Resource shortage	2.44	2.67	3.00	2.70	0.23
C (Environmental and legal)	C1	Natural disasters	4.44	4.56	4.89	4.63	0.19
	C2	Contract management	3.44	3.44	3.89	3.59	0.21
	C3	Regulatory training	2.67	2.89	3.00	2.85	0.14
D (Technical risk, personnel risk and management risk)	D1	Technical barriers	3.44	3.89	4.00	3.78	0.24
	D2	Technological innovation	4.11	4.33	4.67	4.37	0.23
	D3	Personnel turnover	2.44	2.44	2.56	2.48	0.06
	D4	Personnel skills	4.22	4.67	4.89	4.59	0.28
	D5	Management efficiency	4.44	4.56	4.67	4.56	0.09
	D6	Communication and coordination	4.33	4.33	4.44	4.37	0.05

Note: First round, second round and third round scores are the average scores provided by the nine industry experts in each round.

Moving on, nine key influential factors were determined from the second round of expert interviews: safety risk, quality risk, schedule risk, cost risk, environmental risk, legal risk, technical risk, personnel risk and management risk (as shown in Table 3). These factors led to a comprehensive framework for risk assessment and management of DT models, aiding towards achieving a more efficient and safer construction project management. The third round of expert interviews proposed effective response strategies (as shown in Table 4), especially accurate risk assessment, in combination with DT for the listed risks. These strategies offer a comprehensive risk management framework for construction projects through simulation, real-time monitoring, data analysis and feedback mechanisms.

The DTCRAM provides in-depth insights into various risk factors in a project by analysing the mean and standard deviation scores. The model displays risk scores and fluctuations in safety, quality, budget, cost, technology and management, helping to develop effective risk management strategies. In terms of safety and quality, worker safety and construction quality scored high and stable, while equipment safety scored relatively low. Moreover, budget overruns scored high and stable, while project delays and resource shortages scored low and varied widely, suggesting challenges in cost and resource management. On the other hand, natural disasters scored high and stable, while contract management and regulatory training scored low, indicating potential risks in contract execution and legal compliance. In terms of technical risks, personnel risks and management risks, technological innovation and personnel skills scored high and relatively stable, but technical barriers and project management efficiency scored high, indicating that technology and management require more attention and measures. Based on these data analysis outcomes, the corresponding risk management strategies were outlined to cope with various challenges in a project.

Countermeasures evaluation: Relevance analysis

Turning to Delphi, the panel proposed 39 countermeasures for possible actions to overcome the identified strategies. However, there was consensus on only 12 countermeasures out of the 39 identified challenges. Table 5 presents the list of countermeasures, sorted by relevance to the challenges they aim to overcome. The results of the Delphi revealed most of the countermeasures for the strategies. Fifteen countermeasures with this characteristic were identified (as shown in Table 4). Based on the opinions shared by the expert panel, five countermeasures were grouped into one group. In this group, the following countermeasures were detected: risk identification platform for DT (DTIP), risk monitoring platform for DT (DTMP), risk control platform for DT (DTCP), risk decision platform for DT (DTDP) and risk. Furthermore, it is worth highlighting that the experts did not reach a consensus on the countermeasures for the remaining three challenges identified by the Delphi: cybersecurity and data protection (no pass 1), purchase of expensive sensors (no pass 2) and purchase of expensive software modules (no pass 3).

Table 4. Risk strategies in DT

Code		Risk Strategies in DT	First Round Score	Second Round Score	Third Round Score	Mean	Standard Deviation
A (Safety and quality)	A1	To predict and monitor the environment of workers (DTMP)	3.56	3.89	4.11	3.85	0.23
	A2	To simulate and predict possible failures of equipment (DTMP)	3.33	3.78	3.78	3.63	0.21
	A3	To simulate the quality control process (DTCP)	4.56	4.56	4.67	4.60	0.05
B (Schedule and cost)	B1	To control the project schedule and workflow (DTCP)	3.11	3.78	4.00	3.63	0.38
	B2	To control the cost structure and budget allocation (DTCP)	4.44	4.56	4.67	4.56	0.09
	B3	To control the resource demand and supply of the project (DTCP) (no pass 3)	3.22	3.56	3.89	3.56	0.27
C (Environmental and legal)	C1	To identify the impact of natural disasters (DTIP)	4.56	4.56	4.89	4.67	0.16
	C2	To identify and develop solutions in advance (DTIP)	3.56	3.78	4.00	3.78	0.18
	C3	To identify the regulatory execution (DTIP)	3.22	3.56	4.00	3.59	0.32

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Code		Risk Strategies in DT	First Round Score	Second Round Score	Third Round Score	Mean	Standard Deviation
D (Technical risk, personnel risk and management risk)	D1	To simulate technology and identify barriers (DTMP)	4.33	4.33	4.44	4.37	0.05
	D2	To simulate technology and test barriers (DTMP) (no pass 2)	3.78	4.00	4.00	3.93	0.10
	D3	Simulation and prediction of personnel flow (DTMP)	3.44	3.89	4.00	3.78	0.24
	D4	Training and skill enhancement plan by DT (DTCP)	4.67	4.89	5.00	4.85	0.14
	D5	Management process optimisation and efficiency evaluation by DT (DTDP)	4.22	4.33	4.44	4.33	0.09
	D6	Virtual communication platform and team collaboration by DT (DTDP) (no pass 1)	4.44	4.44	4.44	4.44	0.00

Note: First round, second round and third round scores are the average scores given by the nine industry experts in each round.

Based on the three rounds of Delphi scoring data analysis, DT displayed significant advantages in construction risk management. All strategies scored high, especially training and skills improvement plan (D4), which showed its key role in enhancing the overall efficacy of the project with a mean score of 4.85 and a standard deviation of 0.14. The quality control process simulation (A3) scored 4.60 with a standard deviation of 0.05, indicating a high degree of consistent recognition in ensuring construction quality. Identifying the impact of natural disasters (C1) scored 4.67 with a standard deviation of 0.16, highlighting its significance in environmental risk management. Other strategies, such as cost control (B2) and management process optimisation (D5), were highly praised by experts. Overall, DT technology has effectively improved the safety, quality, progress and management efficiency of construction projects through prediction, simulation, monitoring and control and significantly reducing various construction risks.

Case Analysis

The case can improve the application efficiency of DT from actual projects and summarise the risks and strategies that need to be controlled in construction.

Case background

The Thames Tidal Tunnel is a major infrastructure project launched by the London City Government to address the pollution problem of the Thames River. The project includes a 25 km-long underground tunnel for collecting and treating rainwater and sewage. Due to the intricate geological conditions, harsh construction environment and impact on surrounding urban facilities, the project faces huge construction risks. To ensure the success of the project, the project team introduced a construction risk management method based on DT technology.

Physical twin and digital twin

A variety of equipment status sensors are deployed at the construction site to gather real-time data on environmental conditions and equipment status. Sensors are arranged in tunnel boring machines, construction areas and equipment operation areas. Sensors capture environmental risks, technical risks and safety risks in real time to ensure the timeliness and accuracy of data. The DT integrates real-time data from physical twins. Moreover, DT is typically used to identify, screen, monitor and control risks. The identified risks provide a basis for subsequent comprehensive data pool.

Data analysis, decision-making and feedback

The DT simulation identified environmental risks (C), technical risks (D) and safety risks (A) and ed quantitative assessments and analysed their probability of occurrence, including natural disasters (C1), technical obstacles (D1) and equipment safety (A2). Risk events in the project were tracked and the actual effect of DT on risk management was assessed. The comparative analysis revealed the actual effect of risk warning, prevention and emergency response. The baseline occurrence probability (expected probability of occurrence under specific conditions) of A2 in this project was 5%, denoting that the risk probability of equipment failure reduced by 2% (Bricker et al., 2022). The baseline occurrence probability of C1 was 3.0% and the probability reduced by 1.5% (Schooling et al., 2023). These reduction ratios are recorded separately (as shown in Table 5).

Table 5. Probability calculation of key construction risks

Risk Category	Baseline Probability (%)	Probability after DT (%)	Weight
A2	5	3.0	0.40
D1	4	2.5	0.35
C1	3	2.0	0.25

Therefore, for *n* types of risk events, the baseline occurrence probability scores were P1, P2, ..., P*n* and the occurrence probability scores after the application of DT were P1', P2', ..., P*n*'. The formula for the overall risk reduction ratio *R* is as follows:

where *Wi* is the weight of the *i*-th risk event. When *R* = 0.65, thus, the reduction ratio of A2 was 0.80%, the reduction ratio of D1 was 0.50% and the reduction ratio of C1 was 0.25%. The probability of total risk control reduction was less than 1%. The construction risks screened out in the Thames Tidal Tunnel case are as follows: environmental risk (C), technical risk (D) and safety risk (A) – (C1: natural disasters; D1: technical obstacles and A2: equipment safety). Based on these construction risks: C1 – Establish a DT emergency warning system to monitor the signs of natural disasters in time, D1 – Implement regular technical assessments and adjust construction plans and technical processes in time and A2 – Establish a DT predicted equipment safety management system and training plan.

DISCUSSION

The literature review outlines the risks and strategies faced in implementing DT. Upon comparing the literature with the outcomes of the Delphi critical analysis, two main considerations were determined. Based on the Delphi method and case study, the key risk factors and potential risks in construction projects were identified and evaluated. Both the literature review and expert opinions revealed that the key risks in construction risk management mainly focused on worker safety (A1), equipment safety (A2), construction quality (A3), delay (B1), budget overrun (B2), resource shortage (B3), natural disasters (C1), contract management (C2), regulatory training (C3), technical barriers (D1), technological innovation (D2), staff turnover (D3), staff skills (D4), management efficiency (D5) and communication and coordination (D6). This study confirmed the impact of these risks at different project stages and quantified their probability of occurrence and potential impact. These risks matched the literature on construction risk management under DT. However, given that the DT had several characteristics that indicated a higher level of risk, the potential impact of the proposed model was evaluated by combining the expert consensus results and the challenge relevance findings (based on a five-point Likert scale). As a result, a consensus matrix was outlined to clearly define the total impact of the primary difficulties. The difficulties were further classified into four impact quadrants.

The Delphi identified 15 construction risks and proposed solutions to address them. The results of the three rounds of Delphi interviews verified the recommended countermeasures, thus, establishing a foundation for DT. The examination of the selected countermeasures revealed that these effective tactics may be classified into 12 major types. In addition, this study complements studies on the relationship between challenges and countermeasures. For instance, it was observed that DTCRAM can be mitigated by countermeasures that are not necessarily related to the availability of powerful hardware. As a matter of fact, the strategies cover smart data collection systems, availability of powerful hardware, experienced staff, safety training and equipment improvements and optimised construction plans and emergency plans. The experts empirically evaluated and ranked these strategies.

The case study of the Thames Tidal Tunnel project deepens the understanding of the efficacy of construction risk management strategies. Through the application of measures such as system, safety training and equipment improvement, as well as personnel training and communication coordination, the project team successfully coped with multiple challenges and verified both the feasibility and efficacy of these strategies in actual projects. In the project, the DT technology provided key support for construction risk management. Through real-time monitoring and simulation exercises, the project team was able to respond to various risks in a timely manner. In-depth analysis of the case further confirmed the importance and practicality of the construction risk management strategy proposed by Delphi, besides providing useful inspiration for the management of similar projects in the future.

The DTCRAM combines digital modelling, virtual simulation and real-time data analysis. It can accurately identify and evaluate potential risks in the pre-construction stage via digital modelling. By establishing an accurate construction risk assessment model, various construction sites can be simulated. The DTCRAM has the function of real-time monitoring and feedback, which can continuously collect and analyse data during the construction process and discover potential risks in a timely manner. The model can monitor various physical parameters and environmental conditions of the construction site in real time and compare them with the present safety standards, thus, revealing abnormal situations promptly and taking corresponding measures. Such a real-time monitoring and feedback mechanism helps to find and deal with problems in a timely manner during the construction process and minimise the losses caused by risks.

This article introduces the DTCRAM based on the Delphi method and case study. The model integrates real-time data acquisition, virtual simulation and big data analysis, besides integrating a five-layer structure including physical twins, DT, twin models, data analysis and decision feedback to predict and control various risks in the construction process. The DTCRAM can not only quickly identify and assess risks, but also provide effective risk management strategies to reduce project losses and optimise construction efficiency and safety. The DTCRAM has the ability to identify and analyse potential risk factors in the construction process through data analysis and simulation, besides providing targeted risk management suggestions. The model can analyse historical data and real-time data to identify key risks via simulation experiments, providing a scientific basis for risk management decisions. The DTCRAM timely evaluates and predicts potential risks through digital modelling, providing scientific basis and decision-making support for project managers, thereby, effectively controlling construction risk management.

CONCLUSION

The Delphi and case study were integrated in this study to explore the key issues of construction risk management. The Delphi was deployed to identify the influential factors and response strategies for construction risks (the results showed that the expert panel had identified 15 construction risks and 15 effective countermeasures and reached a consensus), which provided an important reference for building a reliable construction risk management framework. Meanwhile, the case study predicted and controlled construction risks (reduced the probability of more than 1% for each project) and improved management efficiency (screened out risk factors). This article proposes an empirical evaluation of DT-related challenges based on their relevance and expert consensus. Countermeasures for implementing DT in manufacturing plants were also verified. The construction risk matrix can help project teams fully understand the risks faced by the project and prioritise countermeasures for risks with high impact and high probability of occurrence. In addition, referring to the case analysis of the Thames Tidal Tunnel project, the application effect of DTCRAM in actual projects had been verified, thus, providing useful inspiration for the management of similar projects in future.

Nonetheless, this study is not without several limitations. The limited number of experts participating in the Delphi method and the influence of subjective opinions of experts displayed certain limitations. Concurrently, the results of the case study might have been affected by the conditions of the specific project and its universality has certain limitations. On top of that, DTCRAM is still in the development stage and it may face some technical and methodological challenges in practical application. Future research can be carried out from the following aspects: (1) further improve DTCRAM to enhance its applicability and accuracy in actual projects, (2) expand the scale of research samples and conduct more extensive verification and application on various types of construction projects and (3) other methods and technologies, such as artificial intelligence and big data analysis, can be explored to further enhance the efficiency and level of construction risk management.

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