A Digital Twin (DT) Framework at Design and Construction Phases

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ABSTRACT: In the construction industry, Digital Twin (DT) encompasses real-time data collection on building models, operational parameters, and other pertinent factors. DT utilizes multidimensional, multi-perspective, and multi-disciplinary simulation processes to enable information mapping via virtual simulations. This study proposes a preliminary framework for applying DT core technologies such as Building Information Modeling (BIM) and the Internet of Things (IoT) into the design and construction phases of building projects, drawing on a comprehensive analysis of DT concepts, technologies, and applications within the construction field. Furthermore, semi-structured interviews and a case study were conducted to validate the framework, with the aim of improving construction site monitoring, quality, and safety. By providing access to a wealth of project information and data, DT can help decrease construction costs, improve quality, and enhance stakeholder management practices.

Keywords: BIM, Digital Twin, Framework, Case Study

1 INTRODUCTION

Despite digitization and information technology becoming unavoidable and drastically altering other industries, the construction sector has maintained a highly fragmented and complex traditional construction paradigm. Traditional construction and management models are no longer able to meet the construction objectives and stakeholder needs of projects as they grow in scale and complexity, have more parties engaged, pose greater risks, and are more challenging to manage, resulting in many problems in the construction industry (Rafsanjani and Nabizadeh, 2021).

According to the Ministry of Housing and Urban-Rural Development, the number of engineering production safety accidents and fatalities nationwide has been increasing year by year (Albtoush et al., 2022). The acceptance of incoming materials is done manually, which often leads to misreporting of the quantities of materials. The management of engineering projects is inefficient and the benefits are not obvious with the traditional methods. As a result, people have been exploring ways to improve resource utilization and productivity, enhance site safety, and reduce project costs and delivery times.

In recent years, DT has been used in multiple fields to link the physical and digital worlds and has the potential to solve the above problems faced by the construction industry. The first DT prototype was developed in 2003 as a "digital version of a genuine object" by University of Michigan professor Michael Grieves (Zhang et al., 2022a). The idea of the "digital twin," which is planning and optimization based on simulation, has the potential to transform both design and manufacturing. DT is perceived as a virtual digital mirror of anything real that can be both digitally reproduced and imitated in how something real would behave in a real setting (Huang et al., 2022). However, there is a general lack of understanding of the concept of DT and how it can be implemented in the construction industry. Thus, the purpose of this study is to provide a general framework for the application of DT in the building design and construction process. The results of this study could potentially help people better understand DT applications and help guide practitioners in implementing DT in the design and construction phases of building projects.

2 LITERATURE REVIEW

2.1 *Research on DT Application in China*

For recent studies, Chen et al. (2022) conducted research on novel coronavirus emergency hospitals. The hospital used a cloud-based web-based collaborative platform during the construction phase to showcase the results of all parties, collect opinions from all parties, and collaborate in real-time with information interchange between all parties while allowing for collaborative management of progress, quality, and cost. A five-layer architecture with primary levels for sensing, transmission, databases, applications, and representation was also designed by Xue et al. (2022) for data exchange in the intelligent building at the project level.

On the usage of digital technologies, the Hong Kong-Zhuhai-Macao Bridge employed a variety of monitoring technologies, including BIM, sensors, GPS, sonar systems, and meteorological systems, to ensure the quality and safety of the transportation and assembly of precast tunnel components (Zhou et al., 2018). Jiang et al. (2021) proposed a framework for intelligent construction site safety management based on a Cyber-Physical system. Simultaneous mapping of virtual buildings and risk data is established with scene reconstruction design, data sensing, data communication, and data physical construction site processing modules to ensure construction site safety.

2.2 *Research on DT Application abroad*

Concurrently, scholars abroad have focused their research on DT technology for construction sites in terms of technology development and application, mainly for the following studies: (1) Machinery automation: Wu and Zhao (2018) investigated the automatic recognition of workers, large construction machinery, and helmet wear based on machine vision and convolutional neural networks. Mneymneh et al. (2017) designed a system framework that applies computer vision technology and integrates multiple hardware and software to automatically detect construction site violations. Asgari and Rahimian (2017) designed a system framework for an integrated supervision platform based on VR, RFID, and other intelligent technologies to identify, record, and pre-alert risks in real-time. Rossi et al. (2019) designed the architecture of a sensor-based automatic mechanical overload recognition system that can be adjusted in real-time for overload peaks in sawmills, concrete mixers, and winches of different types and operating conditions. (2) Technical integration innovation: Some scholars proposed an integrated BIM platform using schedule organization arrangement, and also proposed BIM+GIS for facility management of construction projects (Kang and Hong, 2015; Xia et al., 2022). The application of the BIM+IoT integrated model in assembled buildings has also been studied and reviewed (Li et al., 2018; Tang et al., 2019). The awareness of DT technology in construction projects has increased significantly in recent years; however, the lack of research on its systematic application in the design and construction process remains an unresolved challenge for scholars and practitioners alike.

3 METHODOLOGY

This study adopted a qualitative approach in order to facilitate the establishment of a framework for the application of DT building design and construction. Firstly, a comprehensive literature review was conducted to review and analyze the background and current application of DT technology in the construction industry at home and abroad. In this study, multiple academic publishers, including "Elsevier," "EBSCO," "American Society of Civil Engineers (ASCE), ""Frontiers," "IEEE Xplore Digital Library," "Springer," and "Emerald" were used as the database for articles collection. By searching for specific keywords such as "Internet of Things," "sensors," "digital twins," "BIM," "engineering design," "engineering construction," etc. The titles and abstracts of each article were reviewed to ensure the relevance of the papers by excluding irrelevant content. An initial framework of DT implementation was proposed based on the literature review results.

Subsequently, semi-structured interviews were conducted with six industry experts to refine and verify the proposed framework and determine its range of applications and challenges. These one-to-one interviews were conducted between September 20 and November 10, 2022, and the profiles of the interviewees are summarized in Table 1. The interviewees had been involved in construction for between 1 and 20 years. They are involved in the design and construction process, including schematic design, construction drawing design, bidding, procurement, construction, BIM design, IoT and cloud computing. Overall, the broad coverage and universal participation made the results more objective and rigorous. Accordingly, a hierarchical architecture and a DT technological application framework were finalized based on the results of the literature review and semi-structured interviews. The finalized framework was then further verified through a case study where the DT-related technologies were implemented.

Table 1. Information of interviewees.

Interviewee	Position	Fields of expertise
Interviewee 1	General manager of regional companies, real estate company	Project master planning, control of construction progress, quality, safety, etc.
Interviewee 2	Project manager, construction company	Construction project management
Interviewee 3	Quality officer, the construction unit	Project quality management and material verification
Interviewee 4	Project general manager, the construction unit	Construction site management
Interviewee 5	Safety officer, the construction unit	Pre-control management of site safety protection and civilized construction
Interviewee 6	Business specialist, an Internet Company	Digital twin visualization platform, Internet of things, big data development

4 THE APPLICATION FRAMEWORK OF DIGITAL TWIN

By implementing a DT information management platform, data collected from IoT-enabled devices such as RFID, sensors, cameras, and cell phones can be analyzed for real-time virtual-real interaction and predictive feedback to enhance project visualization and intelligent management. For smart buildings, the initial phase of the DT architecture focuses on tracking and managing the building process, while the maintenance and usage optimization of the physical building entity becomes the primary objective once construction is completed. This study presents a general framework for DT application in design and construction, as depicted in Figure 1, which comprises four main components: the physical space, the virtual entity, the data processing layer, and its integration with the physical environment.

4.1 *Virtual Entity*

The virtual entity of the building includes the digital model and the information system. The implementation of BIM in project management facilitates a more accurate and intuitive understanding of the entire project lifecycle. The BIM's construction simulation enables the team to adjust the original construction plan and schedule to digitally manage the project. A shared project management platform, on the other hand, allows all parties involved in the project to communicate project plans, mitigate risks, reduce project changes, and shorten the construction period, hence improving productivity (Wang et al. 2022). In addition, the BIM's complete information on building materials is automatically imported into the asset management system, eliminating the need for manual data entry and reducing time and labor costs associated with data preparation during system initialization.

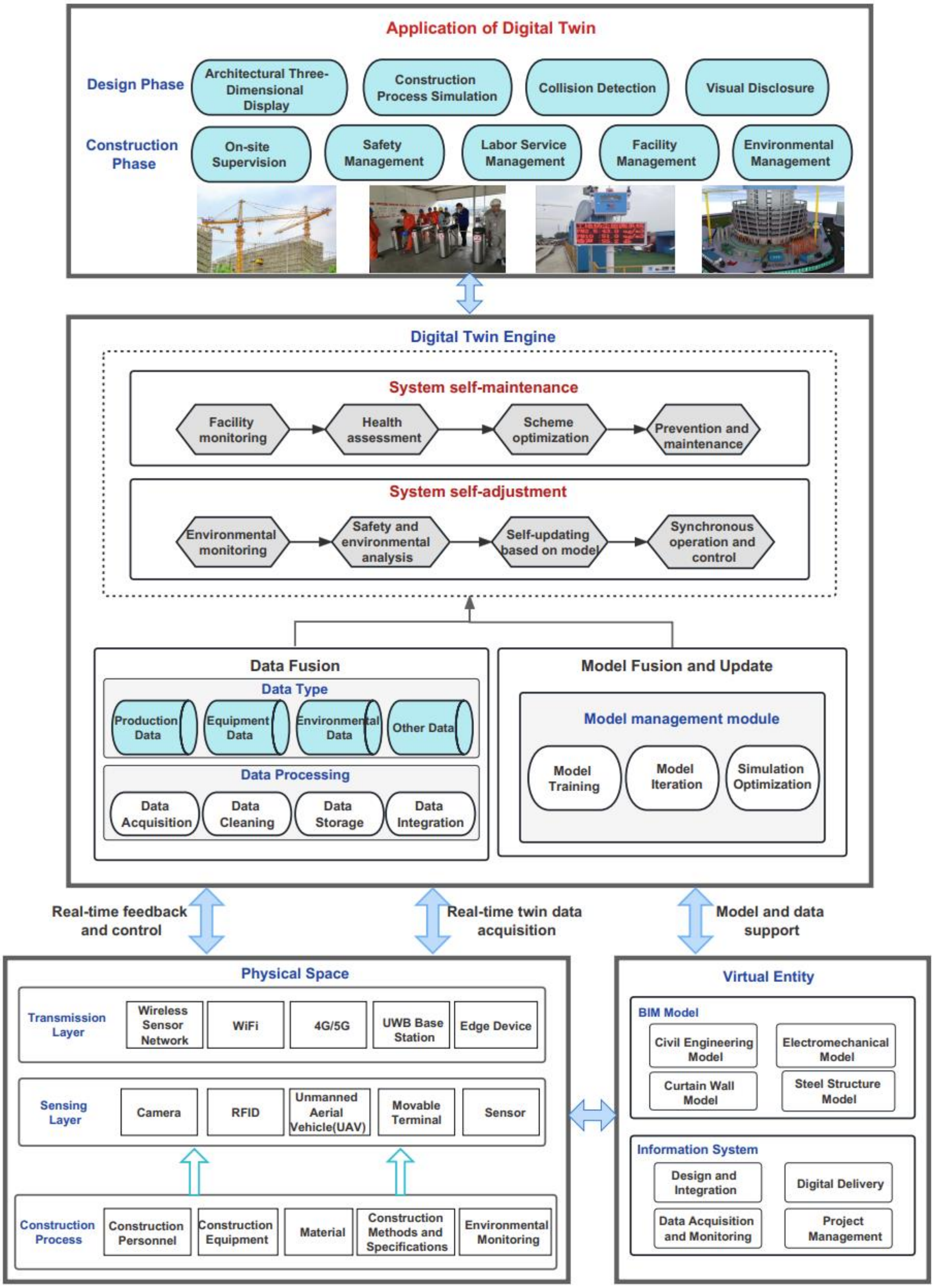

Figure 1. Application framework of the digital twin in design and construction.

4.2 *Physical Space*

The physical world of the building digital dual system consists of two parts: building process tracking and building facility management. Based on the on-site building process, it is sensed via IoT and transmitted to the DT engine for data processing and analysis. The perception layer mainly relies on IoT. IoT is a network that connects any construction-related personnel and objects to the Internet by installing various IoT sensor terminals at construction work sites by agreed protocols. By serving as a network for communication and information sharing, it enables intelligent identification, positioning, tracking, management, and monitoring.

The IoT generates three main layers: (1) comprehensive perception, through the use of sensors, RFID, two-dimensional code, and other collection technology, at anytime and anywhere, to obtain on-site human and machine data; (2) reliable transmission, through the communication network, the Internet, real-time access to data, to achieve instant interaction and sharing; (3) intelligent processing, through the use of cloud computing, big data, and other intelligent computing technology, to analyze and process massive amounts of data and to extract useful information. In the construction site, a series of sensor devices can be used to monitor and maintain the site in real-time, while the use of RFID tags on construction personnel helmets or work clothes can achieve real-time positioning and safety control of workers.

Besides, data transmission is mainly through wireless networks and cellular networks, and UWB base stations can also be used for data transmission. The site information collected by the sensors will be transmitted to the data processing layer for analysis.

4.3 *Digital Twin Engine*

The DT engine, including the fusion of models and data, implements intelligent functions as well as services and applications of DT technology in building design and construction. The two main categories of data that will be stored in this layer are data related to physical space and data related to virtual space. The main categories of data from the physical space include information about equipment, materials, workers, and the environment at the construction site, etc. Most of the data from the virtual world are simulated, including assessment and forecast data and decision data.

Data acquisition, data cleaning and mining, data storage and data integration are all included in the data processing layer. Data acquisition is an interface that uses devices to collect external data and transfer it to the system. Sensors and cameras are data collection tools. The data being collected are various physical quantities that have been converted into electrical signals, such as temperature, wind speed, pressure, water level, etc. Most of the data collected are instantaneous or characteristic values over a certain period of time (Zhang et al., 2022b). Data cleaning and mining are required to extract real and usable data from a huge amount of data by filtering and "denoising". Data integration is the process of bringing together interrelated, distributed, and heterogeneous data sources, allowing users to access them transparently and increasing the effectiveness of information sharing and consumption, while helping to maintain the overall consistency of the data sources. Combining multiple data sources in a single data store (e.g., a data warehouse) facilitates subsequent data mining efforts.

The primary method for validating DT models is simulation, which could verify the validity and accuracy of modeling physical entities. Simulations can primarily reflect the state of physical entities over time as long as the perceptual data are complete and accurately modeled.

4.4 *Application Layer in the Physical Environment*

The application of feedback in the physical environment is mainly reflected in the following aspects.

On-site monitoring: The DT can provide users with an interface that can display construction site conditions and information in real-time, enabling remote video monitoring of the site, remote reception of site alarms, and remote voice dialogue with the site for commands. Managers can get a real-time view of the construction progress and production operation process on-site, as well as remotely monitor the safety of materials and personnel on-site, allowing for remote project supervision.

Personnel management: Personnel information can be collected based on RFID technology, and the information card should contain the basic personal information of construction personnel, thus enabling the positioning and tracking of site personnel on site and the management of personnel's daily attendance records. This can help project managers grasp the personnel statistics of each site area in real-time and understand the distribution of personnel.

Equipment management: Through the visualization of the equipment running status interface, the moving process can be continuously visualized and tracked in real-time throughout the whole process, showing the basic information, distribution, and operation of special equipment (loaders, excavators, tower cranes, etc.) in the whole area for the management staff, providing timely and precise work information to the competent departments, construction parties, supervisors, and operators. It also displays records of equipment use, faults, and maintenance so that management can replace equipment in time and avoid delays due to equipment faults.

Progress management: The model data is obtained in real-time by combining the data for the BIM model progress plan, and the associated process progress plan is exported following the model.

Environmental management: The DT can display real-time PM2.5, PM10, noise, temperature, humidity, wind speed monitoring, the trend of PM2.5, PM10, and noise monitoring data, and whether the relevant alarm value is exceeded. It is easy for the management to grasp the environmental situation of the site in real-time and take timely measures such as spraying and dust reduction.

Safety management: Through the use of sensors to collect real-time data on the operation of tower cranes, lifts, etc., the monitoring equipment will automatically terminate the dangerous movements of the lifts in the event of an early warning or alarm, effectively avoiding and reducing the occurrence of safety accidents (Zhang et al., 2022a).

5 CASE STUDY

The case study targeted a residential and ancillary facilities renovation project, which has a large site area of 202,000 square meters and a total building area of 874,700 square meters. Given the vast size of the project, there are numerous high-risk factors, including deep foundation pits and climbing frames. Furthermore, with up to 41 subcontractors working concurrently, managing safety presents a significant challenge. The distances between different areas of the project create difficulties in information transmission, which in turn pose challenges for construction management coordination. To address these concerns, the project has implemented digital management using BIM and a smart site information platform. This implementation enables the digitization of the entire engineering design and construction process, allowing for site monitoring, safety management, labor management, equipment management, and environmental management. The system organization is comprised of several layers, including the data collection and sensing layer, data transmission layer, data storage center, command center, standard interface and data exchange layer, platform construction, and application layer. These layers align with the DT technology framework presented in Section 4, thereby supporting the practicability of the framework.

The case study demonstrates the application of DT to manage the operation of tower cranes, personnel, and safety issues in construction projects. The system adopts sensor-based data acquisition, data fusion, wireless sensor networks, and remote communication technology to achieve efficient and comprehensive safety monitoring of tower cranes. The system features real-time monitoring and sound and light warning alarm functions to prevent collision incidents and automatically suspends tower crane operations during an alarm event. During the construction of the main project, six tower cranes were installed, and the platform provided a means for managers to accurately monitor the daily work efficiency of each tower crane and the project's progress. Safety and quality management were primarily ensured through human inspection and supervision by safety officers and labor team safety officers. The intelligent management of personnel, equipment, and safety through the platform resulted in a 25-day reduction in construction time and labor cost savings of 250,000 RMB.

6 DISCUSSION

After conducting interviews with multiple experienced managers and professionals, it was found that they were all well-versed in various aspects of the framework, including BIM, site construction, and IoT. Some interviewees had extensive experience in the entire process. Upon summarizing the feedback, all respondents agreed that the framework had a positive impact on building design and construction management. Specifically, interviewees 1, 2, and 4 found the framework to be a well-developed and logically structured theoretical process. Interviewee 5 highlighted the significant impact of the framework on improving safety management on construction sites. For instance, integrating IoT and RFID technology through cameras, tower crane ball machines, and AI alerts has resulted in greater efficiency and reduced workload for safety officers and project managers. The use of such technology has also minimized the time spent traveling to and from buildings for safety checks.

In addition, Interviewee 1 said that environmental management in the framework can effectively help construction sites improve environmental management and achieve green construction. Real-time detection of PM2.5 and other environmental pollutants through the platform saves labor costs and can also effectively protect the health of construction workers and other site staff, in line with the national requirements for ecological civilization and the goal of green construction. Interviewee 4 pointed out that the use of BIM technology can reduce process changes by carrying out drawing checks and model optimization in advance, carrying out construction simulations and process interpolation checks in advance, reasonably preparing schedule plans and reserving time for schedule risks, and arranging supporting task plans in advance to ensure that there are no nuisance works, material shortages, or mechanical hold-ups on-site, thereby achieving cost savings. Respondents 2 and 4 mentioned that the framework could improve communication and efficiency between the various parties involved in the construction, including designers, constructors, supervisors, owners, suppliers, and the project team on site, effectively avoiding the single-party communication problems of traditional construction parties and improving organizational efficiency.

Interviewee 6 pointed out the problem that the IoT is not closely linked to the Internet during practical applications. Therefore, to address this problem, the authorities concerned still need to strengthen the organic interconnection between the IoT and the Internet and enhance the degree of integration between the two to optimize the construction of DT technology on construction sites (Oke and Arowoiya, 2021). Interviewees 1 and 4 raised the importance of personnel training and stated that their companies have now started to implement a training policy for construction personnel, organizing regular safety education and training, and developing reasonable education plans according to different shifts to improve the quality of work and safety management. In addition, VR real-life experience activities are now available on the project, which can help construction workers have a realistic experience of the construction process and reduce losses caused by workers' technical irregularities.

7 CONCLUSION

This paper presents a comprehensive analysis of the current applications of digital technologies, including RFID, GIS, BIM, and VR, in the design and construction phases of construction projects. Through literature review and interviews, a framework for the application of DT technology is developed and its feasibility is verified and analyzed through case studies and further interviews. Results indicate that the proposed framework could potentially bring significant benefits to construction projects in several areas, such as personnel management, environmental management, safety management, equipment management, and quality management. Furthermore, the implementation of the framework leads to the reduction of safety hazards, improved efficiency of hidden hazard identification, and increased safety of engineering personnel, thereby resulting in a reduction of construction time by 25 days and a decrease of an average of RMB 150,000 per year in labor costs. Overall, the findings of this study contribute to the smooth implementation and efficiency of project construction.

The current investigation exhibits two noteworthy limitations. Firstly, the subjective selection of interviewees may have induced bias in the analysis, leading to less comprehensive coverage of specific issues. In order to mitigate the potential for subjective judgment in subsequent inquiries, researchers are encouraged to gather precise data on the application of DT intelligence platforms directly from construction sites and enterprises. This would enhance the reliability of the analytical results. Secondly, the generalizability of the case study outcomes is uncertain. Therefore, future research should expand the scope of inquiry to encompass a broader range of data to attain universal applicability of the findings.

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