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Digital Twin-Based Construction Project Management Integrating Progress Monitoring with Safety Control and Resource Coordination

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Abstract. Construction projects are characterized by long cycles, numerous stakeholders, and constantly shifting site conditions. Managers need current information on progress, safety, and resource use. Traditional methods fall short in meeting these demands. Data acquisition is slow, multi-source integration is weak, and real-time status updating rarely happens. Digital twin (DT) technology links physical engineering assets to digital models and field data. This linkage provides a way to monitor and manage construction processes dynamically. This paper adopts a literature synthesis approach combined with representative case analysis to examine the technical foundations of DT in construction projects. The work summarizes principal applications from three angles: construction progress monitoring, construction safety control, and construction resource coordination. Existing applications show that DT can link building information modeling (BIM) models, sensor data, unmanned aerial vehicle (UAV) imagery, and equipment operation data to actual site conditions. This supports progress deviation identification, safety risk assessment, and resource utilization monitoring. Notably, different scenarios impose different requirements on data types, collection frequency, and model updating methods. Practical applications also face constraints. Data quality, system integration, implementation cost, and continuous model updating are all critical factors. DT in construction projects must be configured to specific management demands and site conditions. Only then does it enhance practical applicability in construction management.

Keywords: digital twin, construction project management, construction progress monitoring, construction safety control, construction resource coordination

1. Introduction

Construction projects tend to have long cycles. The processes are complex, the participating parties are many, and site conditions keep changing. During implementation, management personnel need timely information on progress, quality, safety, and resource consumption. Only then can personnel respond to site issues and make sound decisions. However, traditional approaches rely heavily on manual inspection and periodic meeting reports. Relevant information ends up scattered across separate systems. Some critical data fail to capture actual site changes fast enough, and this lag

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affects decision-making. In recent years, technologies such as building information modeling (BIM), the Internet of Things (IoT), sensors, and digital twin (DT) have entered construction engineering management. DT establishes dynamic correspondences between physical engineering assets and digital models. It maps real-time data from field sensors and images into virtual models. The result is faster information acquisition on site, and a new technical handle for construction process monitoring and management decision support.

Several studies have explored DT in construction project management from different angles. Some scholars built digital twin models for construction sites using BIM and sensor data. These studies analyzed the basic concepts of DT and how it relates to BIM [1, 2]. In progress management, one line of work paired DT with data mining to predict schedule deviations and task completion times [3]. For quality and safety, studies used DT to bring together multi-source monitoring data, analyze construction quality status, and flag on-site safety hazards through real-time data [4, 5]. Other research combined DT with IoT and machine learning to monitor and predict construction equipment operational efficiency and material consumption in real time [6]. A few studies also brought unmanned aerial vehicle (UAV) and computer vision (CV) technologies into the DT framework. These technologies were tested against specific engineering cases to examine whether such applications worked in construction management. The reviewed studies show that the application approaches and technical maturity of DT differ considerably across management tasks. Progress, quality, safety, and resource management each call for different things. That is why a categorized, in-depth analysis by management task is needed.

This study combines literature synthesis with representative case analysis to investigate DT in construction project management. The paper starts by introducing the fundamental concepts of DT and its technical foundations in construction projects. This covers how DT relates to BIM and what supporting technologies such as IoT, sensors, UAVs, and CV actually do. From there, the paper analyzes the principal application approaches and representative cases of DT from three perspectives: construction progress monitoring, construction safety control, and construction resource coordination. For each direction, the research progress and technical characteristics are summarized. The paper closes by discussing the current problems and limitations in practical applications and outlines where future development should head.

2. Digital twin technology in construction projects

2.1. Basic concepts of digital twin

DT goes beyond digital modeling of engineering objects. It places great emphasis on data connection and dynamic updating between physical engineering assets and digital models. In construction projects, the mapped objects can be the buildings, construction equipment, specific construction zones, or even individual construction operations. One review sorted the applications of DT in the construction industry into several directions: BIM integration, structural system integrity monitoring, facility management, site monitoring, logistics processes, and energy consumption simulation [5].

A DT system usually has three core components: the physical engineering asset, the digital model, and the data connection. The physical asset generates real state changes during construction. These include structural deformation, equipment operation, material consumption, and personnel activities. The digital model represents the engineering object and its construction process. BIM usually forms the basis for this model. Sensors, IoT devices, and construction management systems handle data transmission between the physical and digital models. The role of these devices is to

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keep the two synchronized [6]. In practice, the model granularity and updating frequency of a DT system depend on two things: the management objectives of the project and the sensing capacity available on site.

BIM and DT are related but are not the same thing. BIM mainly represents the geometric information and engineering attributes of buildings. It focuses on model establishment during the design phase and information management during the construction phase. DT goes further. It emphasizes dynamic data connection and continuous updating between physical engineering assets and digital models. BIM can serve as the digital model foundation for DT. However, DT usually needs integration with sensors, IoT, and real-time construction data to reflect what is actually happening on site [2, 6].

2.2. Data and technologies supporting digital twins

DT in construction projects draws on multiple types of data. These include BIM model engineering information as well as construction schedule plans and actual data, structural and environmental monitoring data from sensors, equipment operation status data, personnel and material allocation information, and site imagery from UAVs and camera devices. Each data type reflects a different facet of the actual conditions on site. Previous studies collected physical quantities such as structural stress and temperature through sensors for site condition monitoring and anomaly warning [7]. Other research tapped IoT sensors to obtain construction equipment operational efficiency and material consumption data [8].

Getting and integrating these data takes several supporting technologies. BIM provides the model foundation for DT. It holds the geometric information and attribute data of building components. Sensors collect on-site physical quantities like structural stress, temperature, and displacement. UAVs and camera devices capture site imagery. CV techniques then analyze and recognize these images. IoT carries data from various sensors and devices to the platform. One study built a comprehensive monitoring and sensing system alongside a DT platform in a large-scale water conservancy project [9]. Another combined point cloud scanning with UAVs. That team employed artificial intelligence (AI) algorithms to denoise and complete point cloud data, then performed spatial registration with BIM models to quantify construction progress [10]. Cloud platforms round out the picture by providing the infrastructure for data storage, computation, and visualization.

The core of DT application is not just collecting more data. What matters is establishing effective associations between field data and digital models, and keeping the models synchronized with the physical state. When field data flow into the digital model, managers can compare the planned state against the actual construction state and spot schedule delays, quality deviations, or resource allocation anomalies right away. This is what sets DT apart from traditional information display or reporting systems. The mapping and updating mechanism from data to models gives construction management decisions dynamic, real-time information support.

3. Applications of digital twins in construction project management

3.1. Progress monitoring and schedule management

During project implementation, managers need to track actual construction progress continuously and determine whether deviations exist between actual and planned schedules. Traditional progress management leans on manual inspection and periodic construction reports to gather site information. However, report preparation and transmission take time. By the time managers receive the data, site

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conditions may have already moved on. DT can connect the construction schedule information in BIM models with real-time field data. It continuously updates the construction status and identifies schedule deviations by comparing planned and actual states [3]. Some studies also brought in site cameras, UAV imagery, or CV techniques to automatically identify construction completion status. That cuts down the reliance on manual reporting.

Jiang and Chen proposed a technical framework that brings together point cloud, BIM, DT, and AI for construction project progress management [10]. The study collected high-precision point cloud data using 3D laser scanners and UAVs in combination. The authors employed AI algorithms to denoise and fill in missing regions in the point cloud, then performed spatial registration between the processed point cloud and the BIM model. To quantify actual construction progress, the volume ratio of completed components was calculated. Notably, this method directly correlates field point cloud data with the planning model. Progress updating no longer depends entirely on manual reporting. The study went further. It mapped the quantified progress results onto the DT platform, so managers could visually inspect construction completion status and deviation locations. That gave managers data support for construction schedule adjustment.

DT can sharpen the timeliness of construction progress information. Managers get a more intuitive picture of the gap between actual construction status and the plan. When field data keep flowing into the digital model, managers can grasp current progress deviations before construction meetings without waiting for the next report. However, the effectiveness depends on two things: the completeness of field data and how often it gets updated. If data collection lags, or if the digital model and the actual project drift apart, progress assessment accuracy suffers. The processing quality of point cloud data and site imagery also plays a role. It influences how reliably progress can be identified.

3.2. Construction safety management

Construction sites hold many risk factors. Personnel, equipment, temporary structures, and complex working environments all come into play. Safety control requires timely identification of abnormal conditions and potential risks tied to all four. DT can map construction site conditions into digital models. It integrates personnel positioning data, equipment sensor readings, environmental monitoring indicators, and site imagery. This integration enables continuous monitoring of hazardous areas, equipment operating status, and construction operation behaviors [4]. Typical scenarios include safety helmet detection, personnel boundary violation alarms, and equipment overload warnings. In these cases, DT can issue alerts before risks materialize, drawing on camera and sensor data [7]. Compared with traditional safety officer inspections, DT covers a larger range of construction areas. It is not tied to inspection schedules and frequencies.

Kang et al. studied virtual simulation methods for construction processes under complex wind fields [11]. The research object was a cable-stayed-suspension bridge. The bridge sits in an estuary area with strong winds. During the main girder lifting stage, wind loads directly affect construction safety and alignment control. The team built a high-precision wind field prediction model for the bridge site area using a coupled Weather Research and Forecasting (WRF) and computational fluid dynamics (CFD) method. Wind speed, structural response, and construction sequence data all went into the digital model, which was used to conduct wind-induced vibration analysis during the lifting stage. The DT framework integrated three levels: virtual geographic environment, bridge twin model, and simulation modeling. By simulating the structural state at different construction stages, the study predicted how the main girder would behave under different wind speed conditions. The

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predicted displacement and internal force variations gave quantitative support for construction scheme adjustment and lifting window selection.

DT pulls together construction site information that would otherwise stay scattered. It brings it into a digital environment. That makes timely anomaly detection possible and supports safety management. When structural response data, wind speed data, and construction sequence information are continuously updated in the digital model, managers can assess safety risks during the construction process without having to trace causes after accidents happen. However, complex construction environments can hamper sensors and visual recognition. Practical engineering applications also encounter other issues. Data reliability, equipment deployment cost, and personnel privacy all come up. Each of these can slow the adoption of DT in quality and safety management.

3.3. Construction resource management

Construction projects demand rational allocation of resources. Materials, mechanical equipment, construction personnel, and funding all need to be in the right place at the right time. The efficiency of resource utilization directly affects project cost and construction schedule. DT can combine construction plans, equipment operation status, material information, and quantity data. It dynamically records and analyzes resource demands and actual utilization across different construction stages [8]. One study built a three-layer system architecture under the Engineering, Procurement, and Construction (EPC) model. The three layers were the infrastructure layer, the digital twin platform layer, and the intelligent application layer. This architecture transformed the design BIM into the construction BIM using the Industry Foundation Classes (IFC) standard. It achieved automatic quantity calculation and dynamic resource management [12]. The key contribution was extending design information directly into the construction resource management phase. That shortened the cycle of quantity verification and material plan preparation.

Dai et al. developed a DT-based smart construction system for long-distance water supply projects under the EPC model [12]. The case study was the “Three Northern Counties” water supply project in Langfang. The system collected operational data from construction equipment like pipeline welding machines through IoT. Managers used it to monitor equipment utilization efficiency. Le et al. took a different but related path, constructing a DT architecture integrating BIM and IoT for a prefabricated and assembled superimposed station in the Jinan rail transit system. The result was integrated management of construction resources, progress, and quality [13]. Both studies show that DT can link resource utilization to construction progress. Managers can monitor material consumption and equipment operating status by construction operation and zone.

DT can make resource information more transparent. Managers can analyze resource utilization alongside construction plans and site conditions together. That gives managers a basis for resource scheduling and construction organization optimization. In the digital model, managers can review material consumption, equipment operation, and personnel allocation for each construction operation without separately consulting equipment management systems, material ledgers, and construction logs. However, different project management systems may use different data standards. Data integration among BIM models, material management systems, and equipment monitoring systems remains a challenge in practice.

4. Discussion

The principal role of DT in construction project management is to keep connecting the physical engineering asset, the digital model, and construction site data. This connection provides managers

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with more timely information on site conditions. Compared with periodic reports and manual inspection, technologies such as sensors, UAVs, CV, and IoT provide more continuous data sources for digital models. Based on existing applications, this data connection serves construction progress assessment, safety risk analysis, and resource utilization monitoring. However, different management tasks have different requirements. Data types and updating frequencies vary by task. Progress management leans on the correspondence among site imagery, point cloud data, and planning models. Safety management pays attention to structural status, environmental conditions, and personnel and equipment information. Resource management links data on materials, equipment, and construction plans. In practice, DT effectiveness depends on more than the model itself. Reliable acquisition and prompt updating of field data matter just as much.

Currently, DT in engineering sites still faces practical limitations. Construction project data come from many places. BIM models, sensors, UAV imagery, equipment management systems, and material ledgers all feed in. However, these systems differ in data formats, collection frequencies, and management approaches. Information integration is difficult. Construction sites change fast. If model updating speed cannot keep pace, deviations creep in between the digital model and the physical project. Sensor deployment, platform construction, and maintenance all add to project costs. For smaller-scale projects or those with weaker digital foundations, a complete DT system may not make economic sense. Another issue is that different participating parties use different software and management systems. Data sharing faces barriers related to data standards and management permissions. These issues together affect whether DT can be applied continuously throughout the project lifecycle.

Future applications should focus more on how DT connects to practical construction management. The technical functions of platforms and models are not the whole story. For projects with diverse data sources, unified data interfaces and model standards can help reduce redundant conversion and improve information sharing among BIM, IoT, and construction management systems. Field data updating can go further. Integrating it with automated collection, CV, and intelligent recognition would cut the lags and errors that manual entry introduces. The scope of DT implementation should also match the project. Project scale, management demands, and digital foundations all factor in. Not all projects need the same level of sensing equipment and platform functionality. Only by balancing data quality, implementation cost, and management demands can DT be applied more stably to daily construction management.

5. Conclusion

This paper has analyzed the application of DT in construction project management, focusing on three aspects: construction progress monitoring, construction safety control, and construction resource coordination. Existing research shows that DT can link BIM models, field sensors, UAV imagery, and equipment operation data to actual construction conditions. It reflects progress changes, safety risks, and resource utilization more promptly during the construction process. The data and technologies at work differ across scenarios. Progress management focuses on comparing the planning model with actual construction status. Safety management combines environmental and structural conditions for risk assessment. Resource management emphasizes the informational links among materials, equipment, and construction plans. The effectiveness of DT in practical engineering depends on field data quality, model updating speed, and how well different systems coordinate. Construction environments change fast. Incomplete data collection or delayed model updating reduces the reliability of management results. Platform construction and equipment deployment add implementation costs too. Therefore, the application of DT in construction projects

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must be configured to specific management demands and project conditions. That is how to select an appropriate technical scope. Future research can push further on automated collection and sharing of multi-source data. It can also strengthen integration among different project management systems. The goal is to let digital models reflect construction site changes more stably and provide continuous data support for project management. These findings can serve as a practical reference for engineering teams when selecting a digital twin configuration that matches specific management demands and implementation conditions.

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