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Research on Collaborative Management of Construction Schedule and Risk Assessment Integrating BIM and Digital Twin

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Abstract. With the continuous expansion of engineering construction scale and the increasing complexity of construction environments, traditional construction management models have gradually revealed problems such as information lag, slow response and low collaboration efficiency in schedule control and risk assessment. Building Information Modeling (BIM) technology integrates and visually represents engineering information through three-dimensional models and plays an important role in construction organization and schedule simulation. However, BIM models usually rely on static data and cannot dynamically reflect real-time site conditions, making it difficult to meet the needs of real-time management and risk prediction in complex projects. Digital twin technology establishes real-time mapping between physical entities and virtual models, and combined with the Internet of Things, cloud computing and big data analytics, enables dynamic perception and predictive analysis of engineering states, providing a new technical approach for the collaborative management of construction schedule and risk. Taking deep foundation pit construction as a typical engineering node, this paper uses literature analysis and theoretical research to discuss the application mechanism of integrating BIM and digital twin in schedule and risk collaborative management, focuses on their roles in real-time data collection, multi-party collaborative decision-making and risk early warning, and proposes a data-driven collaborative management framework. Research shows that digital twin can effectively make up for BIM's deficiencies in dynamic updating and prediction, realize the linkage management of construction schedule and risk assessment, and improve engineering safety and management efficiency, though there are still shortcomings in data standards, cost input and technological maturity.

Keywords: digital twin, construction schedule, risk assessment, collaborative management, intelligent construction.

1. Introduction

Traditional methods of construction schedule control in the context of conventional engineering management practices are usually developed on the basis of construction plans and complemented with manual recording. In the meantime, the risk assessment largely depends on the engineering

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experience and periodical on-site checks. Moreover, schedule management and risk control are not usually conducted in a way of interaction and coordination, and risk can build up as the construction progresses.

The use of BIM technology has enhanced the degree of engineering information management to some extent. BIM can be used to achieve the visual simulation of the construction processes and support the optimization of the construction organization schemes by developing three-dimensional information models and introducing the time dimension [1]. However, BIM relies mostly on pre-input information, and model changes are not always on the same pace as the construction itself, so it cannot react to the changes on the site in a timely manner. Moreover, BIM is primarily applied to visual analysis in the context of risk management and has rather low dynamic risk prediction capacity [2].

Digital twin technology is a technology that has been slowly implemented in the engineering profession with the development of information technology. Digital twin creates a digital representation of the physical objects and pushes model changes with real-time information to attain dynamic monitoring and predictive analysis of engineering conditions [3]. Digital twin has a high level of real-time performance, data-driven operation, and excellent predictive capabilities compared with BIM.

Thus, BIM and digital twin technology integration can be used to create a collaborative structure of the construction schedule and risk assessment management system and achieve the shift to the dynamic management paradigm as opposed to the traditional static management one [4].

2. Literature review

2.1. The status of BIM technology in research

As one of the essential methods of attaining construction informatization, BIM technology focuses on the incorporation and demonstration of information throughout the entire life cycle of the engineering project through the use of digital models [1]. Specifically, 4D BIM includes a time dimension to create a visual image of the construction process that helps to optimize construction plans, as well as to plan the organization of project time rationally.

Nevertheless, the recent studies have generally found some limitations to the use of BIM in the construction stage. First, all its data is in the initial design phase and the model updates are by hand, which means that it is not easy to reflect real-time dynamic changes on the construction site. In another, although BIM is good when it comes to information expression and visual analysis, it relatively lacks in terms of real-time monitoring and dynamic decision-making tasks [2,5]. Such simple modeling characteristics can be expected to create discrepancies between the digital models and the real construction circumstances under complex engineering situations, thus diminishing the accuracy of the management decision-making.

2.2. Status of digital twin technology research

The technological concept of digital twin was introduced by Grieves whose main idea is to achieve full life cycle management of systems by creating dynamic mapping relationship between physical objects and virtual models [6]. As information technology advances, the digital twin has found its way into the engineering construction field over time, although it started in the manufacturing industry. The relevant literature indicates that digital twin incorporates the Internet of Things, cloud computing, and big data analytics in order to provide real-time perception and dynamic updating of

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the engineering states [3]. This technology is primarily used in engineering construction to monitor construction, early warning of safety and equipment management, which can greatly enhance accuracy and reaction speed of engineering management [7]. According to some scholars, digital twin can be applied during the operation and maintenance phase as well as the construction phase to ensure data management is achieved during the engineering life cycle [4]. All in all, the use of this technology in the engineering profession remains in its infancy with poor standards in data specifications, systems integration, and modes of application [5,8].

2.3. Studies on BIM and digital twin integration

Current literature mostly concurs that BIM and digital twin have a lot of complementary relationship. BIM is concerned with organized engineering information expression whereas digital twin is concerned with data-driven operation and dynamic updating [4]. A recent bibliometric analysis indicates that there has been an evident tendency of digital transformation in the technology application in construction planning and scheduling between 2015 and 2025. BIM combined with AI and digital twin is a research hotspot as the fundamental part of data integration [9]. BIM offers planned baseline in schedule management as well as digital twin monitors actual performance and compares deviations. BIM is used in risk assessment to primarily identify potential risks, whereas digital twin achieves risk prediction and early warning by analysing multi-source data [10].

3. Collaborative management of construction schedule and risk assessment with digital twin

3.1. Selection of engineering node: deep foundation pit construction

One of the most risky major processes of urban engineering is the deep foundation pit construction, which is a complex of the following aspects: the stability of the soils, the control of the ground water, and the safety of the environment around the construction site [7]. In the meantime, the construction processes at this phase are complicated and the evolution is easily influenced by outer settings and the organization of the construction, with intense uncertainty, which is highly representative of the realistic need of joint management of construction timetable and risk.

Using a typical example of a deep foundation pit project in a urban subway station, the depth of excavation is typically 15m to 25m, and the surrounding environments are typically existing buildings and municipal pipelines, so there are high demands on the deformation control. Traditional monitoring data are a valuable data base of the digital twin system [10]. In terms of construction organization, there are strict sequential and coupling relationships of all links of deep foundation pit construction. Any delay or anomaly in one of the links can cause a chain reaction and it is critical to consider implementing digital twin technology to achieve dynamic monitoring of the whole process and joint control.

3.2. Dynamic management mechanism of construction schedule based on digital twin

Within the digital twin framework, a closed-loop construction schedule management is attained by the process of perception transmission modeling analysis, and the main working mechanisms are as follows:

(1) Data Collection and Integration: In the construction site, there are monitoring devices that are placed to monitor various aspects including displacement, structural stress and the environment around it. The layout plan of these devices is optimized in accordance with the principle of key parts first, that is, the collected monitoring data is targeted and reliable [7]. This data collected at the site

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is sent to the cloud platform via IoT gateways; it is then sent through data cleaning and outlier removal processes and combined with the BIM model through a single interface thus forming a direct component-data related relationship [10].

(2) Dynamic Model Updating: In order to maintain the digital twin model consistent with the real-life scenario at the construction site, a time-step updating mechanism is embraced. The model is constantly updated based on real-time on-site data which ensures that it captures the most recent developments in the construction site in a timely fashion. This mechanism will offer a strong background of analysis on the schedule by comparing real-time data against historical data to determine the development trends of the schedule [4].

(3) Schedule Deviation Analysis and Prediction: The actual progress of construction based on the on-site monitoring data are compared against the planned schedule generated by 4D BIM to determine the specific schedule deviation. Prediction models made based on time series analysis are used to predict the future developments of the project. In case of risk of delay in the critical path of the project, the system will automatically send forward an early warning and propose recommendations on resource adjustment, thereby achieving the transformation of construction schedule management to a new level of post-event statistics to a real-time monitoring + trend prediction [9].

3.3. Multi-source data analysis and prediction mechanism for risk assessment

Multi-source data fusion The digital twin system achieves transformation between a risk management system as a passive response and active early warning with the following core mechanisms:

(1) Risk Identification and Data Correlation: Multi-dimensional data in the construction process is combined to create a risk identification system, decompose the overall effects of different factors on engineering safety, and precisely find the risk triggering conditions [7].

(2) Construction of Risk Assessment Model: The combination of threshold method and data-driven method is implemented. The thresholds of the safety controls are determined in accordance with the specifications and standards, whereas the empirical model is determined on the basis of the past data and the levels of risk are scientifically classified [10].

(3) Risk Prediction and Early Warning Response: Trend analysis of the monitoring data is carried out using regression analysis and other techniques to estimate the likelihood of the safety thresholds being reached in future [3]. When risks are identified, the early warning information is immediately sent to the concerned individuals, and it aids in the disposal recommendations, including structural reinforcement, construction sequence modification, or high-risk operations suspension to minimize the risk of safety accidents [7].

3.4. Optimization of collaborative management framework for construction schedule and risk

Contrasting the above working mechanisms, the collaborative management model that is suggested in this paper comprises of six fundamental components, namely, data collection, data transmission, model updating, condition analysis, risk prediction, and coordinated decision-making. The key features of the framework can be summed up in the four following aspects:

(1) Data Flow Path: An entire transmission loop is closed, which can be illustrated as on-site monitoring data to collection system to cloud platform processing to BIM model integration to analysis module computing to decision output. This type of design can ensure timeliness and integrity of information transmission [5].

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(2) System Architecture Logic: The design assumes a three-tier design made up of the perception layer, platform layer and the application layer. Among these, the perception layer is utilized to accomplish data collection; the platform layer is in charge of data processing and dynamic update of models; and the application layer offers the decision support services including schedule control and risk assessment. The communication between all the layers is done via standard interfaces and this is effective in enhancing scalability and stability of the entire system [10].

(3) Schedule-Risk Coupling Mechanism: A single data platform is employed to achieve the profound integration of the schedule management and risk control. After the risk level has been detected to rise, the system will automatically change the construction schedule to avoid the risk of accumulation. In case any construction accelerating and other schedule changes can lead to increased safety risks, the system will issue early warnings in real-time, so creating a two-way feedback system [9].

(4) Comparison with Traditional Management Models: The proposed framework achieves full advancements such as automatic data collection, real-time information update, data-driven decision-making, and built-in collaborative management as compared to conventional modes. These transformations significantly enhance the level of efficiency and safety of construction management [4].

4. The constraints and optimization directions of digital twin in collaborative management of construction

4.1. Core limitations

(1) Data Quality Control: Multi-source data collection is usually not based on common standards and accuracy. Noise and abnormal values are likely to be produced in complex construction environments, and will decrease the accuracy of the latter data analysis [5].

(2) Model Updating and Computing Cost: Digital twins models are updated at a high frequency, which needs many computing resources. This can cause delay in response of the system in large-scale engineering projects. Nevertheless, merely decreasing the model accuracy will also influence the reliability of the analysis results [5].

(3) Risk Prediction model applicability: In the real-world engineering application, the issues that can be encountered with the use of complex algorithms include inadequate data samples and over-fitting. The prediction models are not very universal because of the magnitude of the variations among projects [9].

(4) Customization of Cooperation Systems: The information systems of various units involved do not have standardized interfaces that can facilitate the effectiveness of sharing. In the meantime, the traditional management modes inertia inhibits effective application of collaborative decision-making [5].

(5) Application Cost and Popularization: The first construction requires a lot of investments in the sensors, platform development and other hardware and software [7]. Moreover, the unprofessionalism of digital talents in the construction sector poses challenges in marketing this technology to small and medium-sized projects [4].

4.2. Optimization paths

(1) Data Standardization and Quality Control: There is a need to encourage the standardization of data collection rules and the format of data. Abnormal value identification and data cleaning can be

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optimized using machine learning and other technical tools, to enhance the reliability and availability of data [4].

(2) Accuracy and Computing Efficiency of Models: One can adopt hierarchical modeling, where important parts are represented by highly accurate models and non-essential parts are appropriately simplified [10]. Simultaneously, a dynamic update scheme is established: the frequency of updates is enhanced during the important construction phases and suitably decreased during stable intervals, in order to enhance the overall efficiency of the system in terms of operation [7].

(3) Engineering Applicability of Prediction Models: Prediction models should be chosen that are simple and easy to interpret as much as possible to minimize the reliance on data and difficulty of application [3]. The ability to generalize the model can be improved by generating data on several projects and finding the optimal model parameters [9].

(4) Collaborative Management Adaptive Mechanism: Cohesive data interface standards and information sharing platforms ought to be constructed to manifest the interconnectivity of systems of all participants [10]. Based on this, management processes can be further streamlined, roles can be clarified and the limitations brought about by traditional organizational inertia can be broken [2].

(5) Application Cost Reduction: Modular design may be employed to design functional modules based on the size of the project, in order to be able to control the investment cost [5]. Simultaneously, digital talents can be enhanced by enhancing the training of professionals, which can enhance the technical applicability of construction enterprises [2].

5. Conclusion

This paper is based on the integrated control of building schedule and risk evaluation. It analyses the application features of BIM and digital twin technologies, and discusses their combined application methodology with taking deep foundation pit engineering as a typical example.

Findings show that BIM is good in information integration and visualization, but not dynamic management and risk prediction. In opposition to this, digital twin compensates these shortcomings with real-time access to data and smart analysis algorithms. The joint use of the two technologies contributes to achieving the coordinated regulation of the construction process and the risk, which improves the efficiency of management and construction safety.

Furthermore, this paper observes that the integrated technology is still limited regarding application cost, standardization of data, and technical maturity. In practice, the system incorporates fragmented data to one system, minimizes decision bias, promotes fine-tuned project management, and enhances the standardization of the industry via ongoing data accrual.

However, management mode transformation is not a process that can be achieved in the short-run and must be carried out in phases depending on the circumstances of the different projects. Improvements to be made in the future can be done by developing unified data standards, combining artificial intelligence algorithms, and reducing the cost of applications. Overall, the suggested model of collaborative management is in line with the digital trend of development of the construction industry and can be used extensively.

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