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Exploration of the Application of Digital Twin Technology in the Construction and Maintenance of Prefabricated Buildings

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Abstract: The modular construction model of prefabricated buildings imposes higher standards for refined and intelligent management of construction and maintenance. Existing building management models face issues such as information fragmentation, rough control, and disconnected processes, making it difficult to adapt to the development needs of prefabricated buildings. This paper, by leveraging the technical characteristics of digital twins, outlines the digital application pathways from the two major stages of construction and maintenance, establishes a technical support system tailored to engineering scenarios, and optimizes the collaborative management model for construction and maintenance. It can provide theoretical references for the digital transformation of prefabricated buildings and refined, full-process control.

Keywords: Digital twin; prefabricated building; construction management; operation and maintenance control; full lifecycle

Introduction

The integrated development of building industrialization and intelligence has driven prefabricated buildings to become the mainstream direction of industry transformation and upgrading. Modular construction methods, with their advantages of energy conservation, environmental protection, efficiency, and intensification, are widely applied in various construction projects. Traditional construction operation and maintenance management models are relatively rough, with poor information interoperability across different construction stages, leading to numerous shortcomings in process control, resource coordination, and equipment maintenance. Leveraging digital twin technology to empower the entire process of prefabricated building construction can enhance the overall management level of construction operation and maintenance, promoting the steady transformation of the construction engineering industry towards intelligent construction.

1. Application Path of Digital Twin-Driven Prefabricated Construction in the Building Phase

1.1 Digital Integrated Application in the Production Stage of Prefabricated Components

Digital twin technology can establish independent digital information archives for various prefabricated components, fully recording core details such as component specifications and dimensions, raw material

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properties, processing steps, and process standards [1]. These information archives can be integrated with the factory processing workflow, enabling systematic coordination of process specifications, dimensional accuracy, and processing procedures for component production, thereby stabilizing the standardized output level of production stages. After the components are manufactured, all production information is uniformly stored and preserved, providing complete data support for subsequent on-site inspection, assembly, and quality traceability. This bridges the information gap between the production and construction phases, achieving effective integration between the front-end manufacturing stage and the back-end construction stage of the building.

1.2 Collaborative Resource Management Application at Construction Sites

The prefabricated construction site encompasses various resource elements such as component materials, construction machinery, workers, and site space. Digital twin technology can integrate all resource elements on the construction site to establish a digital resource management and control system covering the entire site. This system can sort out the distribution locations, usage status, and remaining capacity of various resources, develop scientific allocation plans based on the construction progress, optimize on-site layout and equipment placement, standardize the usage rhythm of resources, reduce resource waste and site conflicts, and improve the overall management efficiency of the construction site.

1.3 Application of Collaborative Management for Construction Process Coordination

Prefabricated construction adopts modular assembly as its core construction method, with each construction process possessing independent operational characteristics. The quality of process interface directly impacts the overall construction progress and work order. Digital twin technology can integrate the inherent construction techniques of prefabricated buildings to organize the sequencing logic and interface standards of key stages such as hoisting operations, module assembly, joint treatment, and reinforcement acceptance. Digital management methods can clarify the scope and execution standards of each process, defining the preconditions and postconditions of different operational stages. In multi-workface cross-construction scenarios, it is essential to analyze the intrinsic relationships between processes, regulate the overall work rhythm, and reduce issues such as process disconnection and cross-interference, thereby ensuring a smooth and orderly construction workflow.

1.4 Dynamic Collaborative Control Application in Construction Processes

The construction cycle of prefabricated buildings is lengthy, and the on-site working environment is subject to variability, with construction status continuously evolving as operations progress. Digital twin technology can establish a dynamic construction management and control framework, enabling digital oversight of on-site operations, project progress, and construction status. This framework can update the advancement of each construction phase, identify management gaps and execution deviations in the construction process, and optimize control methods based on digital management logic. The new dynamic management model adapts to the complex and ever-changing on-site scenarios of prefabricated construction, creating a fully controllable construction management system that facilitates the transformation of prefabricated construction management from a static, fixed model to a dynamic, refined one.

2. Application Path of Digital Twin-Driven Prefabricated Building Operation and Maintenance Phase

2.1 Dynamic Control of Building Space and Component Status

The overall structure of prefabricated buildings is assembled from a large number of standardized prefabricated modules, with structural safety and spatial stability depending on the integrity and spatial orientation of various components. Traditional maintenance and inspection rely on manual inspections to identify surface-level damage, providing only basic recognition capabilities while failing to detect subtle issues such as structural deformations, internal material aging, and spatial displacement. Digital twin technology enables the establishment of a dedicated digital management system for the overall spatial system of the building and various prefabricated components, fully recording fundamental information such as spatial structure morphology, component installation parameters, and structural performance

indicators [2]. Through long-term data accumulation and parameter comparison, it identifies trends in structural performance degradation, pinpoints component areas with potential safety hazards, and provides scientific evidence for structural maintenance, component repair, and module replacement.

2.2 Integrated Control of Building Equipment Operation

The mechanical, electrical, HVAC, plumbing, and intelligent facilities installed in prefabricated buildings collectively support the building's daily operational functions. Traditional maintenance methods often involve independent repairs for individual equipment, which disrupt the inherent connections among equipment systems and are prone to creating maintenance blind spots and management loopholes. Digital twin technology can aggregate the basic parameters, operating mechanisms, and functional attributes of various equipment, establishing an integrated equipment management framework. By analyzing the operational patterns and interaction logic of different equipment, it enables the development of a comprehensive anomaly detection and handling mechanism, standardizing the full-cycle management of equipment maintenance, fault diagnosis, and component replacement, thereby ensuring the stable and long-term operation of building equipment systems.

2.3 Intelligent Coordination of Operations and Maintenance Processes

The operation and maintenance of prefabricated buildings encompasses multiple tasks, including structural maintenance, equipment inspection, environmental management, and hazard mitigation. Traditional maintenance models rely on manual experience to organize work content, leading to insufficient overall planning, which often results in redundant operations, overlooked details, and chaotic workflows. Digital twin technology can optimize existing maintenance management models by systematically organizing and scientifically arranging all maintenance tasks. Based on the actual operating conditions of the building, it establishes routine inspection and maintenance plans, defining the scope and standard specifications for each task. It standardizes the implementation procedures and handling protocols for maintenance operations, reducing management deviations caused by subjective human judgment, and building a well-regulated, intelligent, and efficient maintenance management system.

2.4 Continuous Application of Data Throughout the Building Lifecycle

The efficient operation and maintenance of prefabricated buildings heavily rely on the engineering data accumulated in the early stages of the project. Traditional building management models suffer from fragmented data storage and low levels of information integration, making it difficult for data retained during the construction phase to effectively support later operation and maintenance work, thereby limiting the improvement of maintenance management quality. Digital twin technology can aggregate engineering data from the entire lifecycle, including design, construction, and operation and maintenance, to establish a comprehensive building lifecycle data system. By organizing various structured engineering information, it forms a coherent and unified building data resource, providing solid data support for optimizing maintenance plans, tracing hazards, upgrading facilities, and renovating buildings. This drives the long-term and intelligent development of prefabricated building operation and maintenance management.

3. Digital Twin Application Support System in Prefabricated Building Construction, Operation, and Maintenance

3.1 Data Collection and Transmission Support System

The construction, assembly, and maintenance of prefabricated buildings involve diverse information such as component parameters, site conditions, equipment status, and environmental parameters. Complete and accurate raw data form the foundation for the practical implementation of technologies. The data acquisition and transmission support system relies on various front-end sensing devices and collection methods, covering the full range of information needs from construction to post-operation maintenance [3]. This system is responsible for capturing essential data such as on-site construction environment data, component status data, and equipment operation data, providing raw data sources for digital management. A stable transmission link ensures the effective flow of collected information, avoids issues such as data

loss and latency, and establishes an information channel between the physical building and the digital management system, thereby laying a solid foundation for subsequent data processing and model application.

3.2 Digital Model Construction and Iteration System

The digital model construction and iteration system relies on the collected basic building data to complete the establishment of a full-element digital model covering building structures, prefabricated components, supporting equipment, and site environment. Following the modular construction characteristics of prefabricated buildings, the system breaks down independent modeling units, ensuring that the model structure corresponds to the actual building structure. As construction progresses and the building's usage status updates, the system can gradually update the model content and refine details, adapting to the state changes throughout the building's lifecycle. The continuously optimized model architecture can meet the management needs of different construction and maintenance stages, providing a stable carrier for various digital management and control tasks.

3.3 Multi-Dimensional Information Fusion Processing System

The types of data generated during the construction, operation, and maintenance of prefabricated buildings are complex, with differences in the forms of structured parameters, scene information, equipment data, and environmental data. A single data processing method cannot meet comprehensive management needs. A multi-dimensional information fusion processing system classifies, standardizes, and integrates various heterogeneous data. This system can eliminate format and hierarchical barriers between different data types, consolidating scattered fragmented information into systematic data resources. After fusion processing, the information becomes more standardized and complete, capable of adapting to multiple application scenarios such as model invocation, process control, and status analysis, thereby enhancing the overall operational efficiency and application value of the digital twin system.

3.4 Human-Machine Collaborative Operation Support System

Establish a human-machine collaborative operation support system to create a division of labor and mutual cooperation model, clearly defining the work boundaries and functional scopes of digital systems and on-site management personnel. The digital system undertakes basic tasks such as data organization, status aggregation, and process coordination, while management personnel focus on core tasks like decision-making, on-site response, and process control. This system can mitigate the limitations of purely manual management based on experience and compensate for the lack of on-site judgment in purely digital systems, enabling an efficient and coordinated operation model. This ensures the stable implementation and long-term operation of digital twin technology in construction and maintenance scenarios.

4. Optimization Directions for Digital Twin-Enabled Prefabricated Building Construction and Operation & Maintenance

4.1 Optimization of Collaborative Management Model during the Construction Phase

The prefabricated construction system involves numerous participants, with overlapping and interwoven operational phases. Traditional on-site management often adopts a segmented control model. The work content of each team is relatively independent, information exchange channels are relatively closed, and overall coordination is weak. This can easily lead to issues such as uneven resource allocation, disrupted process sequencing, and chaotic on-site work order [4]. Digital twin technology can reshape the collaborative management logic during the construction phase, breaking down the management barriers caused by segmentation. Through a unified digital management framework, it integrates core management elements such as on-site task scheduling, resource allocation plans, and process sequencing logic, coordinating the work pace and scope of various participants. It continuously optimizes the organizational form of construction management, reduces process omissions and management deviations caused by manual subjective control, standardizes the connection standards of various construction stages, and promotes the transformation of on-site construction management toward an intensive and refined mature model.

4.2 Optimization of Management and Control Mode in the Operation and Maintenance Phase

Traditional maintenance operations in prefabricated

buildings commonly face the issue of management lag, with the overall work centered around fault handling and routine inspections, representing a typical passive management model. This type of management approach is difficult to adapt to the modular structural characteristics of prefabricated buildings, and it cannot effectively identify the hidden wear and potential issues of structural components and electromechanical equipment. Digital twin technology can drive a systematic upgrade of the maintenance system, completely transforming the traditional passive management mindset. By leveraging long-term accumulated digital data and state aggregation capabilities, it implements a proactive preventive maintenance management philosophy. It conducts regular monitoring and control of building component conditions, equipment operating status, and indoor and outdoor spatial environments, enhancing the proactive prediction capability of maintenance work, improving the workflow for hazard identification, facility maintenance, and defect remediation, and establishing a more scientific and comprehensive modern maintenance management system.

4.3 Optimization of the Integrated Construction-Operation-Maintenance Coordination Mechanism

In the full lifecycle management of prefabricated buildings, the construction and operation stages have long been disconnected, with two independent management systems operating separately and data resources unable to flow effectively. Engineering data generated during the construction phase can hardly support later maintenance work, while operational data accumulated during the operation phase cannot guide the optimization of construction techniques and building standards, limiting the overall improvement of building management. Digital twin technology can bridge the information and management barriers between these two stages, establishing an integrated management mechanism throughout the entire building lifecycle. By consolidating various data resources and management processes from construction and operation, a complete and coherent engineering management system can be built. Relying on full-cycle data accumulation to optimize construction and operation plans, it enables mutual empowerment between the two stages and improves the full lifecycle management system of prefabricated buildings.

Conclusion

The refined and integrated development of prefabricated building construction, operation, and maintenance relies heavily on the deep empowerment of digital technology. By outlining the specific application pathways of digital twin technology in the construction and operation phases, establishing a comprehensive technical support system, and optimizing traditional management models and coordination mechanisms, industry-wide issues such as information fragmentation and fragmented control throughout the entire project lifecycle can be effectively addressed. Continuously advancing the deep integration of digital twin technology with prefabricated building scenarios can further enhance the full-lifecycle building management system, improving the overall quality and efficiency of prefabricated project construction and operational maintenance.

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