Theoretical Model and Application of BIM-AI-IoT Integrated Construction Progress Management for Smart Residential Buildings

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Abstract. Construction schedule management is fundamental to the success of residential building projects, yet traditional approaches frequently suffer from information lag, fragmented data, poor multi-party coordination, and insufficient proactive risk prediction. To address these limitations, this paper proposes an intelligent construction progress management model integrating Building Information Modeling (BIM), Artificial Intelligence (AI), and Internet of Things (IoT) technologies. The model adopts a four-layer architecture comprising a perception layer, data layer, intelligence layer, and application layer, governed by a core mechanism of "data-driven, intelligent decision-making, and closed-loop optimization." IoT devices enable real-time collection of multi-source site data; BIM serves as the unified platform for engineering information integration and visualization; AI algorithms perform progress deviation identification, duration prediction, and resource allocation optimization. The three technologies form a mutually supportive, closed-loop collaborative system. Simulation experiments on a typical high-rise residential complex demonstrate that the model significantly reduces data collection cycles, improves early warning accuracy, and enhances multi-party collaborative decision-making. Compared with traditional management methods, the proposed model shows clear advantages in real-time perception, proactive risk control, and overall schedule performance, providing a practical solution for intelligent progress management in residential construction projects.

Keywords: Construction schedule management; BIM; artificial intelligence; Internet of Things; residential building.

1. Introduction

Construction schedule management directly affects project duration, cost and overall benefits, and plays an important role in engineering management. Traditional residential construction progress management, which relies on manual record-keeping, on-site verification and experience-based decision-making, has prominent problems such as untimely information transmission, scattered data, poor multi-party collaboration and difficulty in predicting progress risks in advance, and is unable to meet the refined and intelligent management requirements of modern construction projects. With the gradual application of technologies such as Building Information Modeling (BIM), Artificial Intelligence (AI) and Internet of Things (IoT) in the field of engineering construction, new possibilities have been provided for improving progress management methods and enhancing management efficiency [1,2].

Existing studies have explored the application of a single technology in progress management, but there are still deficiencies in the integration of multiple technologies, adaptation to the characteristics of residential construction, and the formation of a BIM, AI and IoT integrated collaborative framework. This thesis integrates BIM, AI and IoT technologies, constructs a four-layer architecture theoretical model, and verifies its feasibility through simulation application, with the aim of providing a reference for intelligent progress management of residential projects [3, 4].

2. Research methods and theoretical basis

2.1. Logic of technology integration

This study is supported by the theories of construction schedule management, systems engineering, information fusion, and intelligent decision-making, and follows the core logic of "data perception - information integration - intelligent analysis - decision output - closed-loop control" to construct a hierarchical technical system. IoT is responsible for the real-time collection and transmission of multi-source dynamic data at the construction site, BIM serves as the carrier for engineering information integration and visualization, and AI conducts intelligent analysis based on the integrated data. The three form a complete technical chain of "bottom-level perception - middle-level integration - upper-level application" to ensure the intelligence and refinement of residential construction progress management [5,6].

BIM, AI and IoT are not simply superimposed, but form a closed-loop integrated system of complementary support, data intercommunication and functional synergy: IoT collects dynamic data of all elements including people, machines, materials, methods and environment, providing real-time data sources for BIM and AI; BIM integrates multi-source information to achieve visual simulation of progress and multi-party collaboration; AI conducts intelligent analysis based on BIM static data and IoT dynamic data, outputs decision-making suggestions and feeds them back to the BIM platform for guidance and control, achieving a closed-loop management of "perception - analysis - decision-making - control".

2.2. Research methods and objects

Four research methods were comprehensively adopted: literature research to clarify the current state and gaps of the technology; system analysis to construct the overall framework of the model; case simulation to verify the feasibility of the model through virtual residential scenarios; and comparative analysis to quantify the management advantages of the model compared to traditional methods. The research object was the construction progress management of high-rise residential buildings, focusing on the construction scenarios with high standardization, flow work, and multi-disciplinary cross-operation. The model research was carried out around core issues such as progress control, deviation warning, resource allocation, and multi-party collaboration. At the same time, the theories of BIM progress simulation, Internet of Things perception and data transmission, machine learning and schedule prediction, multi-source information fusion, and construction dynamic control were systematically reviewed. The application boundaries and coupling relationships of each theory were clarified, providing solid theoretical support for the design of the model's four-layer architecture, data flow optimization, and functional module implementation [6-11].

3. Construction of a theoretical model for BIM-AI-IoT integrated progress management

3.1. Overall design of the theoretical model

Based on the logic of technology integration and the characteristics of residential building construction schedule management, construct a BIM-AI-IoT integrated schedule management theoretical model that is bottom-up and progressive. Overall, it follows the core architecture of "perception - fusion - intelligence - application", taking into account both theoretical scientificity and engineering practicality (‘As shown in Fig. 1’). The model is oriented to address the pain points of lagging information and inefficient collaboration in traditional residential construction progress management. It integrates IoT perception technology, BIM visualization technology and AI intelligent analysis technology to achieve multi-source data intercommunication, functional module collaboration and full-process closed-loop control, ensuring that the model is adapted to the core characteristics of standardized and assembly-line residential construction [1, 3].

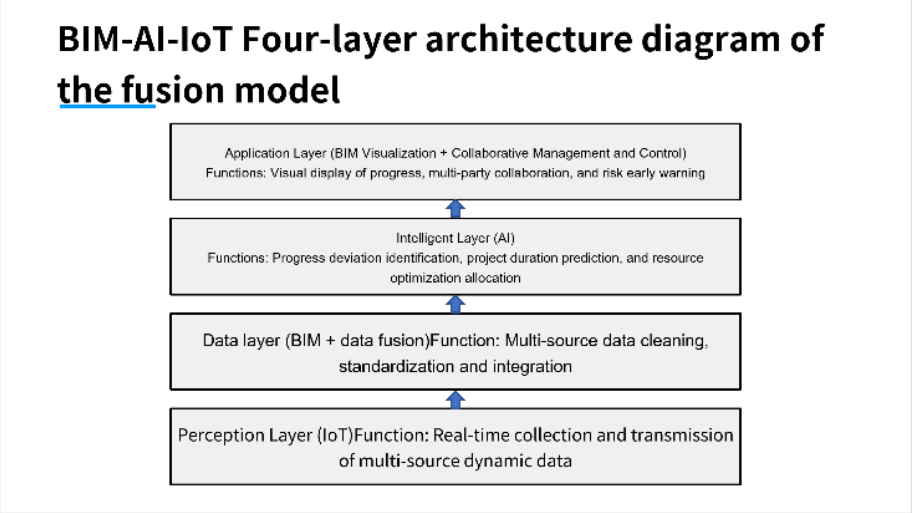


Fig. 1. Four-layer architecture diagram of the BIM-AI-IoT integrated model. (Picture credit: Original)

3.2. Model operation mechanism and core modules

Model operation follows the core mechanism of "data-driven, intelligent decision-making, closed-loop optimization", and builds a dynamic operation system of "perception layer collection - data layer fusion - intelligent layer analysis - application layer control - feedback layer optimization". Real-time data collection of all elements at the construction site is achieved through IoT devices, multi-source data standardization processing and integration are completed through the data layer, intelligent analysis and decision output are carried out through AI algorithms, visual control and collaborative scheduling are achieved through the application layer, and finally control feedback data is returned to complete the closed-loop management [4].

The model consists of four core functional modules: 1. Perception module, which relies on IoT sensors to complete the real-time collection and transmission of dynamic data such as construction site progress, resource status, and environmental parameters, ensuring the authenticity and timeliness of the data; 2. Data fusion module integrates BIM static engineering data with IoT dynamic perception data, standardizes and de-redundanzes multi-source data, builds a unified data resource pool, and solves the problem of data fragmentation [5]; 3. Intelligent analysis module, integrating AI algorithms such as machine learning and deep learning, conducts analysis work such as progress deviation identification, precise construction period prediction, and optimal resource allocation, promoting progress management from passive response to active prediction [2]; 4. Application control module, with BIM technology as the core visualization carrier, implements functions such as progress simulation, multi-party collaborative control, risk warning prompt, control decision output, etc., to enhance the collaborative efficiency of all parties involved in the construction [3].

3.3. Overall operation process of the model

The overall operation process of the model is divided into seven consecutive steps: The first step is data collection, which involves real-time collection and preliminary screening of multi-source dynamic data at the construction site through the perception module; The second step, data fusion, is to integrate the collected dynamic data with the BIM static engineering data, complete standardization processing and redundancy elimination, and build a unified data resource pool; Step 3 Intelligent analysis: AI algorithms invoke data from the data resource pool to conduct analyses such as progress deviation identification, duration prediction, and resource optimization, and output decision recommendations; The fourth step, decision output, feeds the AI analysis results back to the BIM visualization platform to form standardized control instructions; In the fifth step, collaborative control, each participant receives instructions through the application control module to carry out on-site progress adjustment and resource allocation; Step 6, Feedback Optimization: Return the on-site

control effect data to the data layer and update the data resource pool; Step 7 Iterative upgrade: Optimize AI algorithms and model parameters based on feedback data to achieve continuous improvement in model performance.

3.4. Model implementation path and applicable rules

The model follows the implementation path of "layered implementation and gradual landing", which is divided into three stages: The first stage is the basic construction stage, completing BIM 3D model, the deployment of IoT devices and the establishment of the data collection network, and establishing the basic data resource pool; The second phase is the integration and optimization phase, where a data integration platform is built, AI intelligent analysis algorithms are loaded, and multi-technology integration and the coordinated operation of each module are achieved; The third stage is the application stage, where the visualized collaborative control terminal is launched, and the overall debugging and optimization of the model are completed to precisely adapt to the actual scenarios of residential construction.

The implementation should follow four core rules: First, the scenario adaptation rule, the model is applicable to high-rise and multi-story residential projects with a high degree of standardization, frequent cross-disciplinary collaboration, and strict requirements for construction period control; Second, data specification rules: The collected data must conform to engineering measurement standards and a unified data format to ensure comparability and usability; Third, collaborative control rules, which require clear division of rights and responsibilities among all participants and the establishment of an efficient multi-party collaborative management mechanism; 4. Dynamic optimization rules, which require regular optimization of model parameters and AI algorithms in light of construction dynamics, to continuously improve scene adaptability [3].

4. Model simulation application and result discussion

4.1. Simulation scenario settings

To verify the feasibility and engineering applicability of the BIM-AI-IoT integrated progress management model, a typical high-rise residential complex project was selected to build a virtual simulation environment. The simulation project covers multiple high-rise residential buildings and their supporting facilities. It uses a combination of prefabricated and cast-in-place construction techniques and has typical characteristics such as high standardization of residential projects, obvious flow operation features, and frequent cross-collaboration among multiple specialties, which are highly compatible with the applicable scenarios of the model. The scene construction refers to the equipment deployment scheme of Yang Bo et al. In the airport intelligent construction project [4], the BIM 3D model construction, the virtual deployment of IoT sensing devices and the construction of the supporting data acquisition network is completed simultaneously to ensure that the technical logic of the simulated scene is consistent with the actual project.

4.2. Analysis of operational effects

After the model deployment and full-process debugging are completed, conduct a simulation run for the entire construction period of the project. The results showed that the model was stable in operation and could be well adapted to the progress management process of residential construction, effectively addressing the prominent problems of the traditional management model. In the data collection phase, the model achieved automated collection and stable transmission of dynamic data of all elements through IoT sensing devices, effectively shortening the data collection cycle and significantly reducing manual workload; In the intelligent progress control phase, relying on the built-in AI algorithm, the model can complete progress deviation identification and risk prediction based on real-time data, effectively reducing risk response time and improving the accuracy of duration prediction; In the collaborative management phase, based on the BIM visualization platform, real-time information sharing and online collaboration among all construction parties have been achieved,

effectively enhancing the efficiency of collaborative decision-making and basically achieving the application goals of real-time perception, precise control, and efficient collaboration of construction progress.

4.3. Comparative analysis with the traditional model

Select the traditional management model of residential projects of similar scale and process as the control and conduct a comparative analysis from four dimensions: data collection, progress warning, construction period control, and multi-party collaboration [3].

In terms of data collection, the traditional model relies on manual statistics and verification of progress data, which leads to a long collection cycle, large labor input, and makes it difficult to guarantee the timeliness and accuracy of the data. The fusion model achieves automated collection and transmission through IoT devices, significantly improving both collection efficiency and accuracy.

In terms of progress warning, the traditional model is mostly passive handling after deviations occur, unable to predict risks in advance during the construction process, and there is a significant lag in the warning response; The fusion model, based on real-time dynamic data, identifies progress deviation trends through AI algorithms to achieve proactive risk warnings and promote the shift of progress management from post-event handling to pre-event control.

In terms of schedule control, the traditional model of schedule prediction and adjustment is highly dependent on the engineering experience of managers, with a large prediction deviation; The fusion model, based on the fusion analysis of BIM static data and IoT

In terms of multi-party collaboration, the traditional model mainly relies on offline meetings and thesis document circulation to complete, with a long information transmission chain and low collaboration efficiency; The fusion model, through the BIM visualization collaboration platform, enables real-time sharing of engineering information and online linkage approval, significantly shortening the collaborative decision-making cycle.

Overall, the BIM-AI-IoT integrated progress management model constructed in this thesis outperforms traditional management models in all core aspects of progress management and has good engineering application value.

5. Conclusions

Research has confirmed that the multi-technology integration of BIM-AI-IoT can effectively solve the pain points of traditional residential progress management. The four-layer architecture integration model formed by the three technologies realizes the closed-loop management of the entire residential construction progress. The virtual simulation verified its engineering practicability and technical advantages, providing an effective solution for the intelligent management of residential progress. There is still room for optimization in the model's stability in extreme environments, the accuracy of AI algorithms, system lightweighting, and mobile device adaptability. In the future, the model's functional boundaries will be expanded, and digital twin, big data and big model technologies will be integrated to improve the model's functions, promoting its application in more residential projects. At the same time, in combination with the construction characteristics of prefabricated buildings, a standardized and standardized residential construction progress intelligent control system will be ultimately formed.

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