Research on a Digital Twin-Driven Quality Control Framework for Prefabricated Construction of High-Speed Railway Station Buildings

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Abstract. To improve quality control in prefabricated high-speed railway station construction, this study proposes a digital twin-driven framework integrating physical entities, a virtual model, a quality twin data center, and a service platform. By combining multi-source sensing, digital component archives, process-node association, rule-based reasoning, and threshold warning, the framework supports full-process data integration and closed-loop management from component production to on-site acceptance. The Xiong'an Station building project was used for validation through a hierarchical data acquisition scheme and a multi-level virtual model. Results show that the framework achieved 96.4% anomaly identification accuracy, a 12.7 min average warning response time, and a 97.1% rectification closure rate, outperforming manual and BIM-assisted management. Precision, recall, F1-score, ROC-AUC, and PR-AUC reached 0.962, 0.951, 0.956, 0.985, and 0.979, respectively. Statistical tests and ablation analysis further verified its effectiveness and stability. The framework offers a practical approach for real-time, visualized, traceable, and collaborative quality control in prefabricated construction of high-speed railway station buildings.

Keywords: Digital twin; high-speed railway station building; prefabricated construction; quality control

1 Introduction

High-speed railway station buildings feature large scale, complex organization, strong multidisciplinary coupling, and strict quality requirements. While prefabricated construction improves efficiency and reduces on-site workload, it also strengthens the dependence among production, transportation, storage, lifting, assembly, and acceptance. Problems arising in one stage may spread to subsequent processes and affect overall construction quality and operational reliability [1]. Conventional quality control relies heavily on manual inspection, paper-based records, and post-event rectification, resulting in delayed information, weak traceability, limited state awareness, and low coordination efficiency [2]. As a result, it is difficult to meet the demand for full-process and dynamic quality control.

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Digital twin technology provides a promising approach by linking physical entities, virtual models, a quality twin data center, and a service platform to support real-time data acquisition, integrated management, visualized analysis, intelligent warning, and closed-loop control [3]. However, current studies mainly focus on schedule, safety, or general digital applications, and dedicated research on quality control for prefabricated high-speed railway station buildings is still insufficient. Therefore, this paper proposes a digital twin-driven quality control framework and verifies its feasibility through an engineering case.

2 Digital Twin-Driven Quality Control Framework for Prefabricated Construction of High-Speed Railway Station Buildings

2.1 Design Objectives

This study aims to develop a digital twin-driven quality control framework for prefabricated construction of high-speed railway station buildings, enabling efficient interaction among physical construction entities, virtual construction models, the quality twin data center, and the quality control service platform [4]. The framework connects key stages including component production, transportation, storage, lifting, installation, and acceptance, and supports dynamic perception and unified representation of personnel, equipment, materials, methods, environment, and management factors. It improves the real-time availability, integrity, and traceability of quality information, and further enables quality visualization, deviation identification, risk warning, and collaborative response. In doing so, it promotes a shift from post-event correction to process control and from fragmented supervision to closed-loop management.

2.2 Overall Framework Architecture

Given the diverse component types, tightly coupled procedures, complex site conditions, and long responsibility chains in prefabricated high-speed railway station construction, this study establishes a digital twin-driven quality control architecture consisting of physical construction entities, a virtual construction model, a quality twin data center, and a construction quality control service platform [5]. Personnel, equipment, components, environment, and processes are defined as key sensing objects, and multi-source quality data are collected through sensors, identification technologies, and on-site terminals. These data are mapped to the virtual model to synchronize component status, construction progress, and quality information. The quality twin data center supports data aggregation, cleansing, storage, association, and analysis, providing a unified basis for deviation identification, risk warning, and traceability management. The service platform supports practical tasks such as component acceptance, lifting positioning, joint connection, quality inspection, and rectification closure, thereby enabling visualization, collaborative issue handling, and decision support, and forming a closed-loop mechanism between physical and virtual spaces, as shown in Fig. 1.

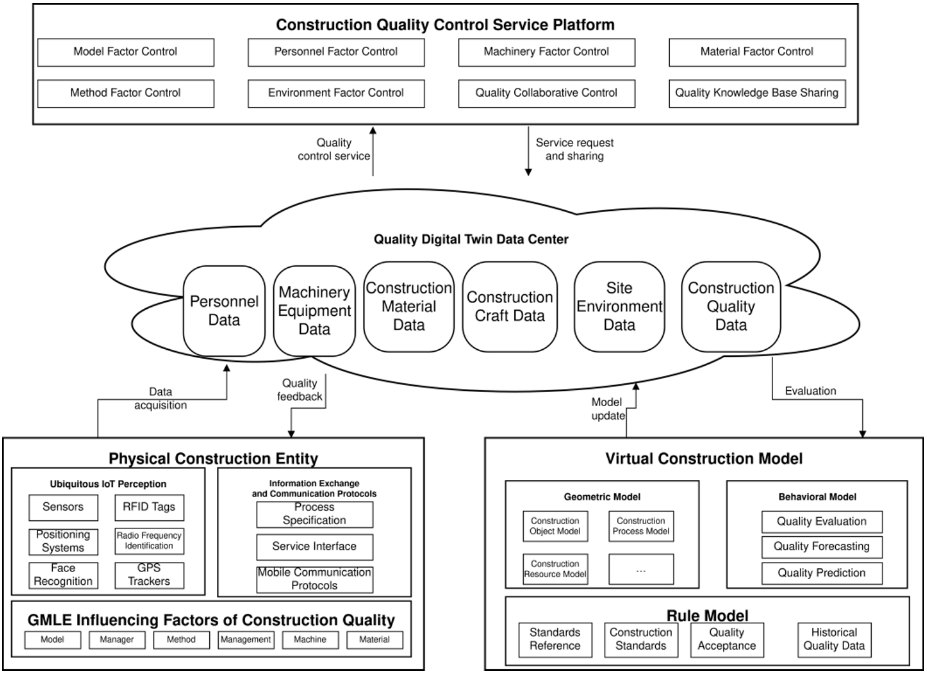

Fig. 1. Overall Architecture of the Digital Twin-Driven Quality Control Framework for Prefabricated Construction of High-Speed Railway Station Buildings

2.3 Perception System of Physical Construction Entities

Prefabricated construction of high-speed railway station buildings involves multiple component types and complex site conditions, making quality states strongly time- and space-dependent. Therefore, the perception system covers personnel, equipment, materials, methods, environment, and management across production, transportation, storage, lifting, installation, joint connection, and acceptance[6]. By integrating RFID, QR codes, video monitoring, sensors, mobile terminals, and positioning technologies, the system captures real-time quality data and forms continuous lifecycle records to support problem localization, responsibility tracing, and process correction.

2.4 Virtual Construction Model Development

Based on drawings, BIM models, and construction plans, the virtual model represents structural geometry, component types, joints, installation relationships, and site layout. It also embeds coding information, material properties, quality standards, process requirements, acceptance rules, and schedule data, forming an integrated model of geometry and rules. Combined with laser scanning, field measurements, and sensing data, the model is continuously updated to remain consistent with site conditions. By incorporating quality evaluation, deviation identification, and risk simulation, it can detect lifting deviation, abnormal joint installation, and process conflicts, providing visual and predictive support for quality management.

2.5 Design of the Quality Twin Data Center

The quality twin data center links physical entities, the virtual model, and quality control services, and serves as the core of full-process collaborative management. It integrates sensing data, BIM data, schedule information, inspection records, rectification records, and historical quality knowledge. Because these data differ in format, granularity, timeliness, and semantics, the center supports unified data access, cleansing, transformation, coding, mapping, updating, and knowledge accumulation. Using component codes and process nodes as the main logic, it builds a full-lifecycle data chain from production to installation and acceptance. It also supports rule invocation, case comparison, abnormal pattern recognition, and warning threshold setting, enabling real-time, coordinated, and traceable quality management.

2.6 Design of the Construction Quality Control Service Platform

The construction quality control service platform is the functional carrier of the digital twin-driven framework, integrating sensing data, model data, rule data, and on-site management needs into a unified service system for the whole prefabricated construction process. Considering the characteristics of station projects, such as multiple component types, long transportation paths, high installation precision, and strict joint quality requirements, the platform adopts a four-layer architecture consisting of an application layer, a functional layer, a data layer, and an algorithm layer.

The application layer supports component tracking, transport and storage monitoring, installation deviation monitoring, joint quality evaluation, and rectification traceability. The functional layer provides quality configuration, analysis, simulation, and decision optimization for visualization, anomaly identification, risk warning, and collaborative management. The data layer centrally manages production, transport, installation, inspection, and historical quality data. The algorithm layer supports deviation identification, joint quality assessment, risk analysis, and rectification optimization. Through the coordination of these layers, the platform converts fragmented quality information into continuous and dynamic control capability, promoting a shift from static recording and post-event treatment to real-time perception, process intervention, and collaborative closed-loop control, as shown in Fig. 2.

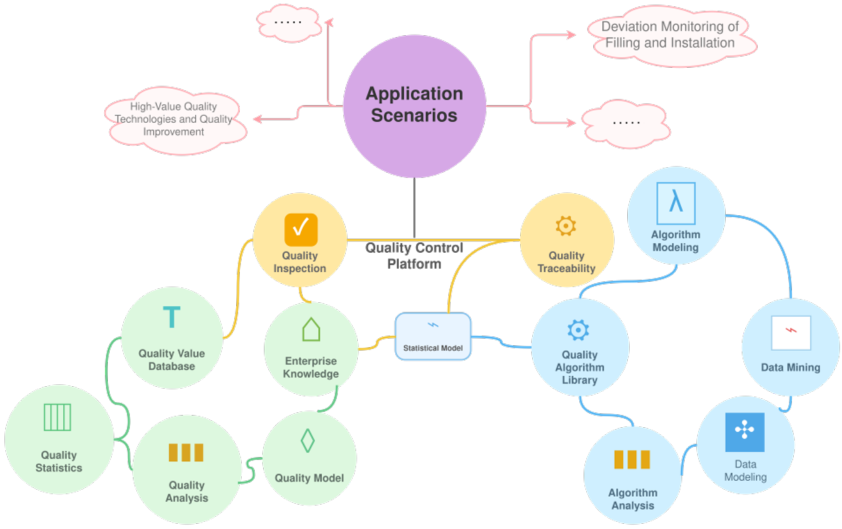

Fig. 2. Fragmented supervision to collaborative closed-loop control

3 Engineering Application Validation

3.1 Project Overview

To validate the proposed digital twin-driven quality control framework, the Xiong'an Station building project was selected as the engineering case. Located in Xiong'an New Area, the project has a total construction area of about 475,200 m², including approximately 150,000 m² of station building area and 109,000 m² of platform canopy area, with a yard scale of 13 platforms and 23 tracks. Owing to its large scale, dense multidisciplinary interaction, and complex interfaces among the station building, platform level, and canopy connection zones, the project involves a long quality responsibility chain covering production, transportation, storage, lifting, installation, and acceptance. Compared with ordinary public buildings, it faces greater risks of delayed information transfer, unclear responsibility, difficult deviation tracing, and low rectification efficiency.

3.2 Data Acquisition Scheme for Physical Entities

A hierarchical data acquisition scheme was established for personnel, equipment, components, procedures, environment, and management records. Data were associated by the dual key of component_id and process_node_id, and each record included timestamp, source type, spatial position, status code, quality label, and rectification index. Over 124 construction days, 18,642 process-node records were collected. After deduplication, clock alignment, and invalid-value filtering, 17,980 valid records were retained, including 2,146 confirmed anomaly samples. The anomaly categories included installation deviation, joint deficiency, process sequence conflict, incomplete quality records, and environmental exceedance.

The sensing layer integrated RFID, QR-code terminals, network cameras, UWB positioning, total station remeasurement, displacement sensors, weather stations, and mobile inspection terminals. MQTT, RTSP, HTTPS/REST, and Modbus TCP were adopted for data transmission. All data were normalized to UTC+8, registered to the BIM coordinate system, and stored in a unified schema including component metadata, process events, sensor observations, image references, and quality-disposal logs.

3.3 Deployment Scheme of the Virtual Model

High spatial complexity and dense quality control points in the project required a virtual model deployment system consisting of one master control model and five sub-models. The master model represented the overall station space and site layout, while the sub-models covered the main structure, steel roof, prefabricated platform components, MEP system, and site organization. Critical assembly nodes and quality control zones were modeled at LOD 400, and ordinary areas at LOD 350. Using the one-component-one-file strategy, 3,248 key components were linked with geometric attributes, inspection data, transport records, installation status, and rectification documents. The deployment configuration of the virtual model is summarized in Table 1.

Table 1. Deployment Configuration of the Virtual Model

Module	Main Content	Update Method
Master Control Model	Overall station space and site layout	Scheduled + event-driven
Structural Models	Main structure, steel roof, platform components, connection nodes	Event-driven
MEP and Site Models	MEP system, storage yards, transport routes, lifting zones, temporary facilities	Scheduled
Component Archive Unit	One-component-one-file mapping and lifecycle records	Real-time
Rule and Synchronization Unit	Quality rules and model–data–platform synchronization	Rule-triggered + timed refresh

For implementation, Revit and Navisworks were used for BIM integration, PostgreSQL/PostGIS for spatial data, InfluxDB for time-series data, MinIO for image and document storage, Redis for state caching, EMQX for message transmission, and Spring Boot plus Vue for business interaction and visualization. The model adopted hybrid synchronization with 10 min scheduled refresh and immediate updates for key events such as component arrival, lifting start, installation completion, and quality reinspection.

Anomaly detection combined a rule engine and XGBoost-based risk scoring. The system included 32 quality rules, 18 warning thresholds, and 54 input features. The dataset was split into training, validation, and testing sets at 70%, 10%, and 20%, respectively, with class imbalance handled by scale_pos_weight = 6.5. Final warnings were generated by weighted fusion of rule-based and model-based results.

3.4 Result Analysis

The proposed framework was evaluated using anomaly identification accuracy, average warning response time, and rectification closure rate, and compared with conventional manual quality management and BIM-assisted quality management. Ground-truth anomaly labels were determined through cross-confirmation of inspection records, measurement or image evidence, and rectification documents. Repeated time-split testing on 10 weekly batches was adopted, and significance was assessed using two-sided paired t-tests.

As shown in Table 2, the proposed framework achieved the best results in all three indicators, with 96.4% accuracy, 12.7 min average warning response time, and 97.1% rectification closure rate, outperforming the two comparison methods.

Table 2. Comparison of Different Methods with Statistical Significance

Method	Accuracy (%)	Avg. Warning Response Time (min)	Rectification Closure Rate (%)
Conventional Manual Quality Management	84.7 ± 1.9 (83.3–86.1)	46.5 ± 4.2 (43.5–49.5)	88.3 ± 1.8 (87.0–89.6)
BIM-assisted Quality Management	90.8 ± 1.6 (89.7–91.9)	28.4 ± 3.4 (26.0–30.8)	93.1 ± 1.3 (92.2–94.0)
Proposed Digital Twin-driven Framework	96.4 ± 1.2 (95.5–97.3)	12.7 ± 2.1 (11.2–14.2)	97.1 ± 1.0 (96.4–97.8)

Note: n = 10 weekly batches, two-sided paired t-test.

Further evaluation introduced precision, recall, F1-score, ROC-AUC, and PR-AUC to assess anomaly identification performance. As shown in Table 3, the proposed method achieved the best results, indicating strong anomaly discrimination without increasing false alarms or missed detections.

Table 3. Classification Metrics of Quality Anomaly Identification

Method	Precision	Recall	F1-score	ROC-AUC	PR-AUC
Conventional Manual Quality Management	0.861	0.834	0.847	0.893	0.871
BIM-assisted Quality Management	0.910	0.892	0.901	0.947	0.932
Proposed Digital Twin-driven Framework	0.962	0.951	0.956	0.985	0.979

The comparison of precision, recall, and F1-score among different methods is shown in Figure 3.

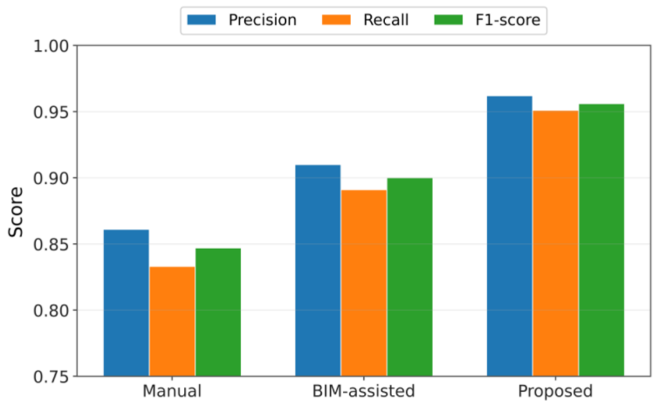

Fig. 3. Comparison of Precision, Recall, and F1-score under Different Quality Control Methods

The ROC curves under different quality control methods are shown in Figure 4, and the PR curves are shown in Figure 5.

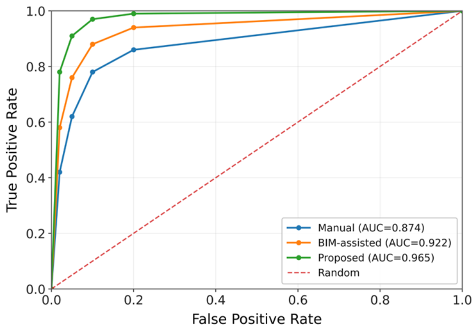

Fig. 4. ROC curves

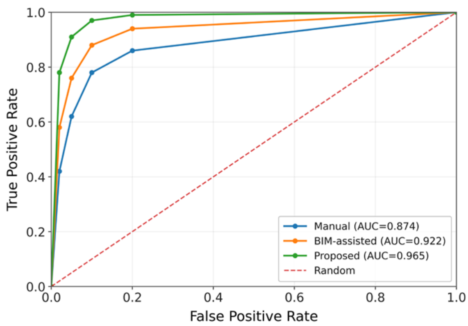

Fig. 5. PR curves

To quantify the contribution of key modules, an ablation study was conducted. As shown in Table 4, removing the event-driven synchronization module increased the average warning response time from 12.7 min to 18.9 min, indicating that timely state refresh is critical for site intervention. Removing the rule engine caused the largest decrease in anomaly identification accuracy, while removing the component archive mapping module weakened issue tracing and responsibility localization, thereby reducing closed-loop rectification performance.

Table 4. Ablation Study Results

Configuration	Accuracy (%)	Avg. Warning Response Time (min)	Rectification Closure Rate (%)
Full framework	96.4	12.7	97.1
Without event-driven synchronization	94.1	18.9	95.0
Without rule engine	92.8	14.3	94.6
Without component archive mapping	94.3	15.8	93.9

4 Conclusion

Engineering validation based on the Xiong'an Station building project showed that the proposed framework improves quality control in complex prefabricated construction scenarios. It outperformed conventional manual quality management and BIM-assisted quality management in anomaly identification accuracy, warning response time, and rectification closure rate, reaching 96.4%, 12.7 min, and 97.1%, respectively. Precision, recall, F1-score, ROC-AUC, and PR-AUC were 0.962, 0.951, 0.956, 0.985, and 0.979, respectively, and statistical tests confirmed the significance of these improvements. The ablation study and stress tests further verified the contribution of key modules as well as the scalability and robustness of the framework. Overall, the proposed framework provides an effective solution for real-time, visualized, traceable, and collaborative quality control in prefabricated high-speed railway station construction.

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