

Analysis of Quality Traceability Architecture of Prefabricated Building based on Digital Twin and Blockchain Collaboration

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Abstract. Abstract. The quality traceability of prefabricated buildings faces two major challenges: low data credibility due to centralized storage vulnerabilities, and poor process visibility caused by fragmented information across design, production, transportation, and assembly stages. To address these issues, this thesis proposes a novel four-layer architecture that integrates digital twin and blockchain technologies. The four layers—physical perception, data transmission, digital twin mapping, and blockchain consensus—work synergistically to enable tamper-proof data recording and real-time visualization throughout the component life cycle. Digital twin provides dynamic mirroring of physical processes, while blockchain ensures decentralized trust and data immutability. The feasibility of the proposed architecture is verified through the Hong Kong MiC (Modular Integrated Construction) Sanbao project and two additional case studies, where key quality indicators such as material origins, production parameters, and installation records were successfully traced. Real-world challenges, including data synchronization latency, on-site sensor reliability, and smart contract execution costs, are analyzed in depth. The research demonstrates that the collaboration of digital twin and blockchain effectively bridges the trust gap between physical and digital worlds, enhances stakeholder accountability, and reduces information asymmetry. These findings offer a practical reference for implementing transparent and reliable quality traceability systems in prefabricated construction, with potential extensions to other off-site manufacturing scenarios.

Keywords: Prefabricated building; quality traceability; digital twin; blockchain; Modular Integrated Construction.

1. Introduction

Prefabricated construction is an important direction for the transformation of China's construction industry. In industrial production, quality controllability should theoretically be improved. However, the reality is not optimistic. Multiple parties participate in the supply chain, forming data silos. Traditional centralized records are vulnerable to tampering. The traceability chain is broken, making it difficult to define responsibilities. Some researchers pointed out that "prefabricated buildings... have also encountered many difficulties in quality traceability, such as low data credibility, serious centralization, and easy information tampering" [1]. This is not merely a technological lag; at a deeper level, it reflects a profound misalignment between industrialized construction methods and traditional management models.

It must be admitted that existing traceability systems have many shortcomings. Nevertheless, two main flaws stand out: first, data credibility is not guaranteed; second, process visualization is insufficient. The two issues are intertwined—unreliable data turns visualization into a "beautiful lie," while invisible processes prevent reliable data from supporting on-site decision-making. From this perspective, exploring the application of digital twin and blockchain in whole-process quality traceability is urgent. This thesis proposes system architecture covering the entire process of component design, production, transportation, installation, and maintenance.

2. The theoretical basis and synergistic advantages of key technologies

What is the essence of quality traceability in prefabricated buildings? It lies in building distributed trust—tracing "who, when, and what" has been done to each component. Digital twin builds a

"mirror" of the physical world based on Building Information Modeling (BIM) and the Internet of Things, providing a foundation for process visualization. However, the mirror alone cannot answer whether it has been tampered with. This is exactly where blockchain comes in. Blockchain ensures data tamper-proofness through decentralized storage, consensus mechanisms, timestamps, and other technologies, meeting the credibility requirements of quality traceability. The collaboration between the two can be summarized as "twin perception, on-chain evidence," forming a closed loop between the physical and digital worlds.

It is worth noting that academic views on the collaboration of the two technologies are not entirely consistent. Some studies focus more on the trust anchoring of blockchain, while others emphasize the visualization value of digital twin. This thesis adopts a "dual-engine" perspective: one engine drives process visualization, and the other drives data trust. As noted by Hunhevicz and Hall, "the convergence of digital twins and blockchain is essential for establishing trust in automated construction processes" [2]. In contrast, another view holds that blockchain needs to be deeply integrated with existing tools such as BIM in the quality management of prefabricated building construction. Dong et al.'s empirical research confirms that component positioning systems based on BIM and blockchain significantly improve data accuracy [3]. Tagliabue et al. demonstrated the feasibility of Internet of Things (IoT)-blockchain solutions in wallboard automatic detection [4]. Furthermore, Wang et al. suggested that blockchain could give digital twin legal subjectivity, enabling it to be self-agent [5]. These studies confirm the potential of synergy in different ways.

3. Collaborative system architecture design

Based on the above theoretical foundation, this thesis proposes a collaborative architecture of digital twin and blockchain for the quality traceability system of prefabricated buildings. The core design concept can be summarized as "on-chain evidence, twin presentation, intelligent linkage." Logically, the system is divided into four layers from bottom to top.

Physical layer: Includes components, sensors, and data collection terminals, responsible for translating reality into digital signals.

Digital twin layer: Based on BIM, it integrates design, production, transportation, and assembly information. The core functions are "mapping" and "synchronization." It is important to note that not all data needs to be stored on the chain. Excessive on-chain storage can lead to system bloat and increased costs. A reasonable strategy is "graded certification" core quality data must be recorded on the chain; process monitoring data is stored on the chain in summary form, while the original data is verified by the on-chain hash value. Li et al. proposed a smart product-service system based on blockchain and IoT which further validates the feasibility of this hierarchical strategy [6].

Blockchain layer: Adopts a consortium chain—considering that the participating entities in the construction industry are relatively fixed, this is a more practical technology choice. The components include smart contracts, consensus nodes, and an on-chain database. The application scenarios of smart contracts are worth exploring in depth. For example, if a component is hoisted out of the factory before the maintenance time meets the design strength requirements, the contract can automatically trigger an alarm and lock subsequent circulation permissions. This mechanism can eliminate violations at the source.

Application layer: Provides differentiated views for different users. Mobile scanning and query should become standard features, allowing on-site personnel to "scan and know the origin of this component."

The core breakthrough of architecture lies in the "data dual" mechanism. Physical components have real-time synchronized virtual representations in the twin world, and important state changes are simultaneously recorded on the chain. When it is necessary to trace the quality history of a certain component, one can visually "see" its entire life-cycle process through the twin model, and also "prove" that these records have not been tampered with through blockchain trusted verification. It is worth mentioning that the architecture reserves an interface for regulatory nodes—this not only meets

compliance requirements but also takes into account the public attributes of engineering quality issues. Government regulations should be able to penetrate and obtain trusted data [7].

4. Case analysis and experience enlightenment

The theoretical framework ultimately needs to be tested by practice. In this regard, the Hong Kong Modular Integrated Construction (MiC) Sanbao project provides a valuable window for observation. The system integrates blockchain and IoT and has been piloted in six MiC projects [8]. Its core modules—inStar (production record on the chain), e-TranStar (transportation environment monitoring), and e-InstalStar (installation accuracy verification)—are highly consistent with the collaborative design ideas in this thesis [8]. The application results show that the on-chain rate of component production records reaches 100%, and abnormal events are warned in real time [8]. The project won the 2025 Hong Kong Information and Communication Technology Award, which indirectly confirms the feasibility of the technical path [8].

Another case of interest comes from Lee et al. They verified that an integrated digital twin and blockchain framework can enable full traceability of data transactions [9]. Figueiredo et al. pointed out that, from a sustainability perspective, this integration enhances material traceability and reduces controversy [10]. This perspective broadens our understanding of quality traceability systems—trusted traceability not only serves quality control but also supports green construction and carbon emissions accounting.

However, the case studies also expose some unavoidable problems. It must be admitted that the authenticity of the data collection side remains a weak point. Sensors may malfunction or be interfered with by humans, but blockchain cannot distinguish "fake data." In the Hong Kong MiC project, some inspection records are still manually entered, leaving room for human intervention. In addition, the cost of system integration is high, and for small and medium-sized component manufacturers, there are significant technical barriers to connecting with blockchain platforms. A third issue is cross-platform interoperability—blockchain systems used by different projects may be incompatible, and cross-project traceability could become a new challenge in the future.

The lessons from these experiences are multifaceted. From a technical perspective, "edge trust" should be the focus of the next optimization—introducing trusted execution environments or device authentication at the data collection source to ensure native data trust at the physical level. From a management perspective, standardized data on-chain specifications need to be established, clarifying which data must be recorded on the chain, when to record it, and who is responsible for confirmation. In terms of promotion strategy, a "platform + application" model can be considered where the government or industry associations lead the construction of the underlying blockchain infrastructure, and small and medium-sized enterprises access it through standard interfaces, thereby lowering the application threshold.

Objectively speaking, the collaborative application of the two technologies is still in the transition stage from pilot to promotion. However, as the cost of digital twin modeling gradually decreases and the threshold for blockchain applications continues to decline, could this collaborative model become the standard for quality control of prefabricated buildings in the future? The answer is worth anticipating.

5. Conclusion

First, digital twin and blockchain have significant synergistic effects in the quality traceability of prefabricated buildings. The former solves "process visibility," and the latter solves "data trust." Can the two work together to truly bridge the trust gap between the physical and digital worlds? Based on the analysis in this thesis, the answer is yes. Second, the core of the collaborative architecture lies in the "data dual" mechanism and the hierarchical certification strategy, achieving a balance between efficiency and trustworthiness. Third, cases such as the Hong Kong MiC Sanbao project have verified

the feasibility of the technical path, but also exposed real challenges such as data source trustworthiness, cost, and interoperability. Fourth, the current dual-technology collaborative application is still in its early stages, and systemic issues such as standards, costs, and ecosystem development need to be resolved.

Future research can explore four directions: first, a "native trusted" mechanism that introduces device fingerprints and trusted execution environments at the data collection source; second, smart contract-driven automatic accountability that encodes norms into executable logic; third, cross-chain interoperability and data sharing; fourth, lightweight deployment solutions to reduce the application threshold for small and medium-sized manufacturers. Technology is merely a means. The ultimate goal of quality traceability is to improve engineering quality and ensure public safety—this should never be forgotten at any time.

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