Hyperledger Fabric-Based Blockchain Application in Modular Construction Manufacturing

Angat Bhatia[1,3], Vafa Rostamiasl[1,2] and Osama Moselhi[1,2]

[1]Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, QC, Canada
[2]Centre for Innovation in Construction and Infrastructure Engineering and Management (CICIEM), Concordia University, Montreal, QC, Canada
[3]Risk Management Department, Hatch, Gurugram, India
angat.bhatia@hatch.com, vafa.rostamiasl@concordia.ca, moselhi@encs.concordia.ca

Abstract –

Modular Construction Manufacturing (MCM) has attracted considerable attention in recent years due to its potential to increase productivity, minimize waste, and improve the predictability of building projects. Despite these benefits, effective coordination and real-time information exchange among multiple stakeholders in the delivery of modular construction remains a significant challenge, particularly in managing production line data for module components. Current data-sharing practices in MCM are often fragmented and rely on manual reporting, leading to inconsistencies, limited traceability, and reduced trust among stakeholders. To address these challenges, this paper introduces a permissioned blockchain method for MCM. The proposed method includes: *(i)* network design, *(ii)* smart contract development, and *(iii)* transaction execution and evaluation. A smart contract (chaincode) is developed to automate the creation, updating, and querying of production data, while enforcing validation rules and access control exclusively among participating stakeholders. The blockchain network is established with two peer organizations representing key stakeholders to facilitate decentralized transaction endorsement. This method ensures consistent ledger synchronization, strengthens data integrity, and provides tamper-resistant and traceable documentation of module component records throughout the production line. The implementation of the proposed method utilizing the wall panel production line data confirms the feasibility of permissioned blockchain-enabled information management in MCM and highlight its potential to support more transparent, reliable, and collaborative production workflows. In addition, it protects data privacy by allowing only authorized project members to participate in and maintain the network.

Keywords – Modular Construction; Blockchain; Hyperledger Fabric; Smart Contracts; Production Data Management

1 Introduction

Modular construction has emerged as a transformative approach within the construction industry, offering significant advantages over conventional construction. By shifting major construction activities to a controlled factory environment, modular construction enhances production efficiency and reduces production line waste (e.g., worker waiting time) [1-2]. In particular, Modular Construction Manufacturing (MCM) enables standardized fabrication of module components (e.g., wall panels) in the production line, supporting higher levels of automation and repeatability [3]. This construction process has become increasingly relevant as governments and industry pursue scalable and sustainable solutions to address housing shortages [4]. Despite its benefits, the MCM process is characterized by fragmented information flows and limited interoperability between stakeholders [5].

Production line managers and on-site supervisors often maintain independent systems to record and exchange information, resulting in inconsistencies and duplicate records. These inefficiencies become more pronounced when stakeholders participate in multiple projects. Considering the dynamic nature of the production line, which requires frequent changes in production line planning (i.e., change orders), and delays/inaccuracies in sharing these module components production information (e.g., estimated process time of module components) propagate downstream, affecting production line planning, on-site assembly sequencing, and project makespan [6]. Moreover, the success of MCM relies heavily on the accuracy, transparency, and coordination of production line information (e.g., start and finish time of module components) shared among multiple stakeholders (e.g., production line manager and on-site supervisor).

The modular construction industry requires a reliable, tamper-proof mechanism to capture and share production data in real time across all participating stakeholders (e.g., production line managers and on-site supervisors). Such an approach must ensure trust, traceability, and data integrity without relying on a centralized system. In this regard, Blockchain has been proposed as a promising solution due to its decentralized architecture, immutability, and built-in consensus mechanisms [7]. Studies have examined blockchain applications in supply chain management, smart contracts for construction payments, and document management for construction applications [8-10]. However, most prior works focus on conceptual frameworks and overall supply chain-level applications, with limited research demonstrating practical blockchain deployment specifically for production-level applications in modular construction. In addition, there is a notable gap in operational prototypes that integrate blockchain with actual production data, smart contract logic, and multi-stakeholders within an MCM environment. Considering the broader adoption of blockchain in the MCM production line, it is necessary to test its potential benefits with a case study. In particular, a smart contract should be designed and implemented to demonstrate its potential to efficiently manage and share production line data to improve the MCM production line process. To address these gaps, this paper proposed a Hyperledger Fabric-based blockchain method for MCM. The proposed method consists of the following procedures: (i) creating a blockchain architecture tailored for MCM, (ii) developing a smart contract for managing module component data, and (iii) evaluating the proposed blockchain method through transaction execution and ledger validation using a MCM case study. The contributions of this study include: (i) a permissioned blockchain network with peer organizations representing key stakeholders (i.e., production line manager and on-site supervisor) in the MCM; and (ii) a custom smart contract (chaincode) is developed to record, query, and manage module components information, ensuring authorized project members to participate in the network and tamper-resistant information management and exchange. It is worth mentioning that Hyperledger Fabric is chosen due to the following reasons: (i) it protects data privacy by allowing only authorized project members to participate in and maintain the network; and (ii) it is an extensible open-source platform that users can customize according to their needs [8].

2 Literature Review

2.1 Blockchain Technology in Construction

Blockchain has recently emerged as a transformative technology that can enhance transparency, trust, and data integrity in construction projects. As a decentralized and immutable ledger system, blockchain enables distributed parties to record transactions securely without relying on centralized authorities [11]. Early construction-oriented studies highlight blockchain's potential benefits in supply chain, contract administration, and automated payment mechanisms [12]. Moreover, blockchain's ability to ensure tamper-proof and auditable records aligns with the construction industry's need for verifiable information exchanges among fragmented stakeholders [13]. However, most blockchain research in construction focuses on supply chains and payment automation, with limited work at the production-line level in modular construction. Moreover, many studies propose conceptual frameworks rather than operational prototypes, and research on permissioned blockchains, such as Hyperledger Fabric in a modular construction production line environment, is limited.

2.2 Digital Technologies for Modular Construction

Modular construction relies heavily on digital technologies to support precision, standardization, and coordination. Building Information Modeling (BIM) enhances design integration and clash detection, enabling improved off-site fabrication planning [14]. Likewise, cloud-based platforms also facilitate data sharing and decision-making across the modular construction lifecycle [15]. Despite these advances, digital systems in MCM often operate as isolated platforms controlled by single organizations, resulting in fragmented and inconsistent production data. Studies note persistent issues, including a lack of interoperability, limited trust in shared information, and difficulty maintaining accurate records across stakeholders [16]. These challenges highlight the need for decentralized solutions that can complement BIM and cloud systems by ensuring secure, tamper-resistant, multi-party data integration.

2.3 Blockchain Adoption for Manufacturing and Modular Construction

Manufacturing research highlights blockchain's role in enabling transparent production monitoring, machine-to-machine communication, and component traceability [17]. Smart contracts have been used to automate quality checks, material verification, and workflow approvals, demonstrating the potential for blockchain to enhance cyber–physical coordination in factory environments [8-10]. Modular construction shares similar challenges with general manufacturing, such as multi-stakeholder interactions, frequent design changes, and strict quality control requirements. In this regard, Blockchain has been proposed as a suitable enabler for secure data exchanges between manufacturers, suppliers, and contractors [9]. However, most existing studies remain conceptual, and few have developed and tested blockchain solutions integrated with real modular production data. In addition, there is a gap in end-to-end blockchain prototypes demonstrating live transactions for module components (e.g., wall panels) production line data.

3 Proposed Method

This paper adopts a structured method to design, implement, and validate a blockchain-enabled information management method for modular construction manufacturing (MCM). As illustrated in Figure 1, the proposed method consists of three main steps: (i) network design; (ii) smart contract (chaincode) development and deployment; and (iii) transaction execution and evaluation. The proposed method begins by designing a permissioned blockchain network (i.e., Hyperledger Fabric) tailored to the MCM process. Subsequently, smart contracts are developed to automate module components (e.g., wall panel) production data transactions (e.g., estimated process time). Finally, the proposed system is evaluated through transaction execution and ledger evaluation.

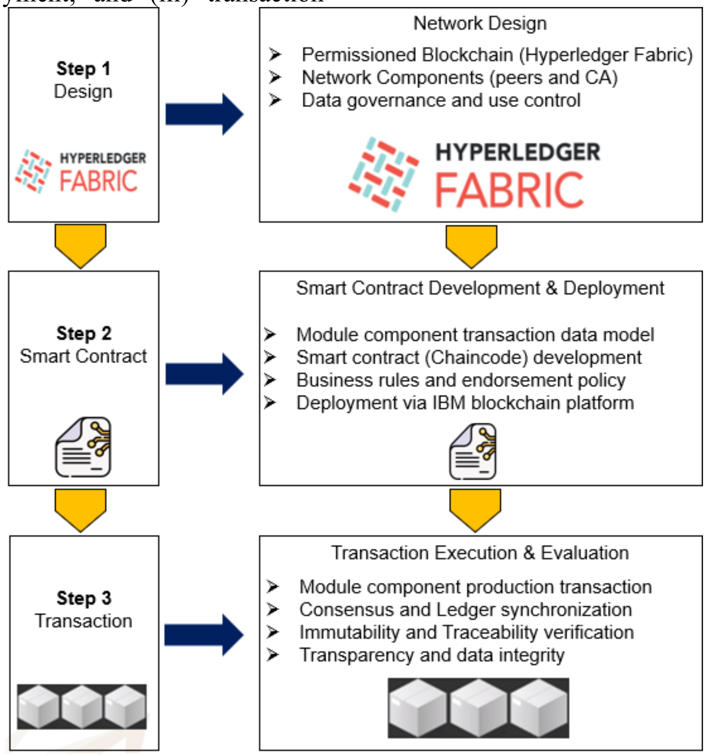

Fig. 1: Overview of the proposed Hyperledger Fabric-based blockchain method for MCM

3.1 Network Design

The first step focuses on designing a blockchain network that supports a secure, transparent, and multi-stakeholder information exchange in MCM. The prefabrication process of module components (e.g., wall panels) was selected as the target use case due to its repetitive nature and reliance on accurate production data. A permissioned blockchain architecture was adopted to ensure controlled access and data privacy among participating stakeholders (e.g., production line manager and on-site supervisor). Core network components, such as peer nodes, channels, ordering services, and certificate authorities (CA), are defined to enable secure identity management, transaction ordering, and ledger synchronization. In addition, data governance rules and access permissions were established to govern the recording, sharing, and querying of production information within the network. This design ensures that production data remain tamper-proof, traceable, and accessible only to authorized participants; thereby addressing common information fragmentation challenges in current MCM.

3.2 Smart Contract Development

The proposed blockchain method incorporates a set of smart contract components to regulate information exchange and data governance in MCM, as illustrated in Figure 2. These components are implemented as executable smart contracts (chaincode) on a permissioned blockchain network and designed to manage participant access, record production line transactions, and support secure data querying. Authorized stakeholders, including the production line manager and on-site supervisor, are registered through a certificate authority (CA) and assigned predefined roles to ensure controlled access to production data. Production-related transactions for module components, such as process time, are validated against predefined endorsement policies and recorded on the distributed ledger following consensus. In addition, query functions are provided to enable authorized participants to retrieve real-time and historical production information without permitting data modification. By formalizing access rules within smart contracts, the proposed components enhance transparency, traceability, and data integrity while eliminating reliance on centralized information management systems.

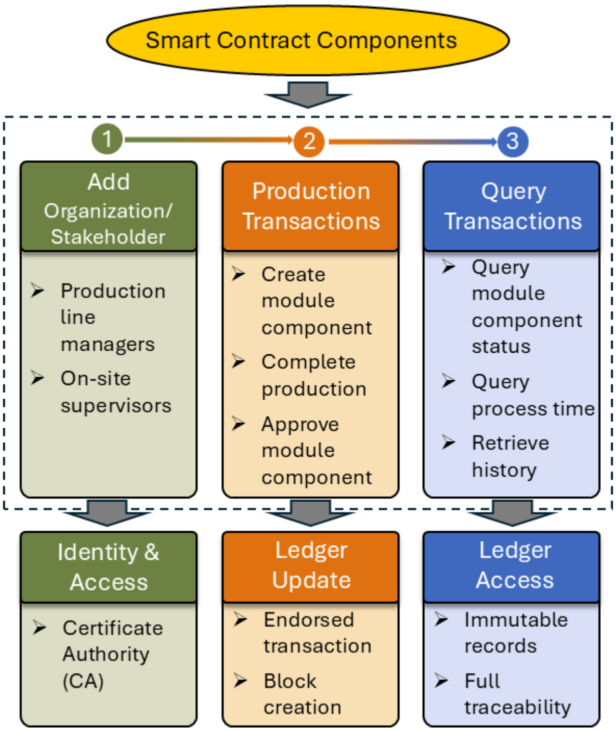

Fig. 2: Proposed smart contract components for MCM

As shown in Figure 3, smart contracts were developed to encode manufacturing business rules governing the creation, update, and querying of module components (e.g., wall panel ID). These contracts ensure that production information is recorded in a consistent and standardized manner while enforcing predefined validation rules. Endorsement policies were specified to require transaction approval from relevant stakeholders (i.e., production line manager and on-site supervisor) before records are committed to the distributed ledger. The blockchain network and smart contract were deployed using the IBM Blockchain platform, which provides a graphical interface for configuring Hyperledger Fabric infrastructure. The deployment process included: (i) installing the smart contract on both organization peers; (ii) approving the chaincode definition to reach endorsement consensus; (iii) committing the chaincode to the channel, making it operational; and (iv) instantiating the ledger to begin recording production transactions. Additionally, the module component data (e.g., number of studs, windows, start and finish times of module components at the workstation) used in the blockchain environment was collected utilizing an RFID system. The process times (i.e., the time required to complete one module component at a given workstation) are extracted using Equation 1:

$$PT_{m,w} = IRT_{m,w+1} - IRT_{m,w} \qquad (1)$$

Where PT is the process time of module component ID "m" at current workstation "w", "w+1" is the next workstation, and IRT is the initial read time of the module component at a given workstation of the production line. The process times are initiated as transactions in the smart contract using a deep neural network (DNN) based prediction model [18]. Hyperparameter tuning—the process of identifying optimum parameters (i.e., number of hidden layers, number of neurons, learning rate and momentum) is performed by employing a genetic algorithm (GA). The optimization objective is to minimize the model's prediction error (i.e., MAE), as expressed in Equation 2:

$$MAE = \frac{\sum_{i=1}^{n} |A_i - P_i|}{n} \qquad (2)$$

Where Ai is the actual process time of a module component, and Pi is the predicted process time of a module component. A detailed discussion of the developed prediction model is beyond the scope of this paper and is reported in a paper by Bhatia et al. [18].

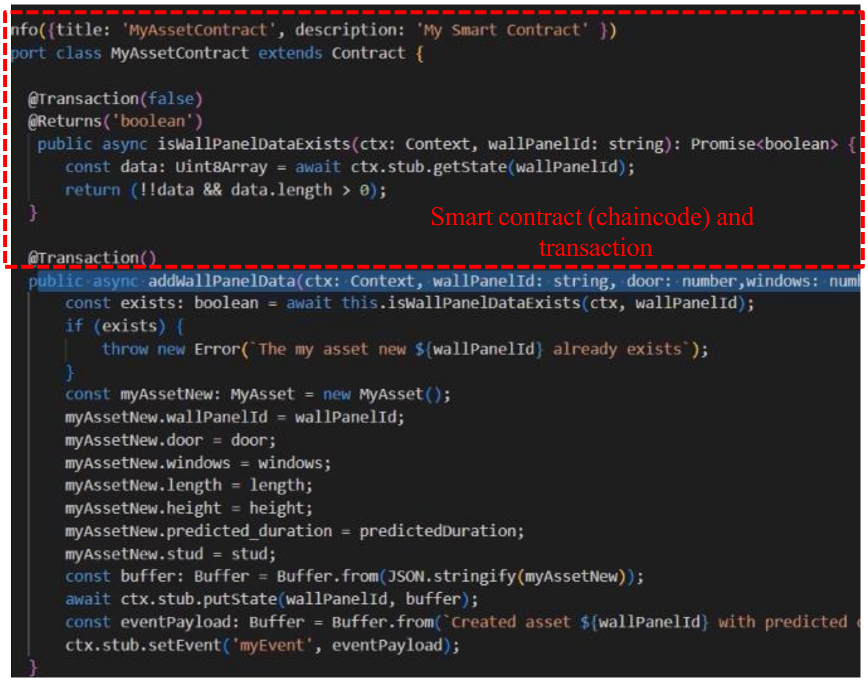

Fig. 3: Snippet of the Smart Contract

3.3 Transaction Execution and Evaluation

The final step evaluates the blockchain network through transaction execution utilizing a case study. Blockchain transactions corresponding to module components information (e.g., number of doors and windows) were executed to simulate real-time manufacturing operations. These transactions were endorsed by peer nodes, ordered into blocks, and committed to the distributed ledger in accordance with the defined consensus mechanism. When transactions were submitted, peers endorsed the transaction according to the network policy, and the ordering service generated a new block. Ledger synchronization across peer nodes was examined to verify the consistency and immutability of recorded production data. The traceability of wall panel records was assessed by querying historical transactions and validating their resistance to unauthorized modification. The evaluation focuses on the system's ability to enhance transparency, ensure data integrity, and support trustworthy information sharing among stakeholders. This demonstrates the feasibility of applying blockchain technology to MCM and highlights its potential to improve information reliability and coordination across production environment.

4 Case Study

The proposed method utilized data from a wood-frame wall panel production line in Edmonton, Canada. The production line consists of framing station, sheathing station, multifunction bridge, window/door installation lines, where windows/doors are installed on the wall panels and transferred to the wall magazine line (i.e., storage area). Process times at workstations were collected by the modular fabricator company using an RFID system. The data for the workstations includes the time between July 2015 and August 2018. As such, it contains 416,950 timestamps (i.e., start and finish times) for wall panels at various workstations and design attributes (e.g., number of studs and number of windows), for a total of 93,660 wall panels. A detailed discussion of the RFID data and the development of predictive model is beyond the scope of this paper and is reported in papers by Altaf et al. [1] and Bhatia et al. [18]. The objective of the case study is to demonstrate the application of the proposed method by deploying smart contracts, transaction execution and validation through data querying to retrieve immutable production line data of a wall panel production line.

Figure 4 illustrates the deployment of the proposed smart contract within a Hyperledger Fabric network using the IBM Blockchain platform. The smart contract definition, including its name and version, was deployed to a dedicated blockchain channel (i.e., Blockchain-4) and approved by two peer nodes (e.g., Org 1 Peer representing production line manager) operated by separate blockchain organizations. Deploying the smart contract across multiple peers ensures that transaction execution and ledger updates are jointly validated in accordance with predefined endorsement policies. This configuration establishes decentralized trust, prevents unilateral data modification, and enables consistent synchronization of wall panel production data across participating stakeholders (i.e., production line manager and on-site supervisor).

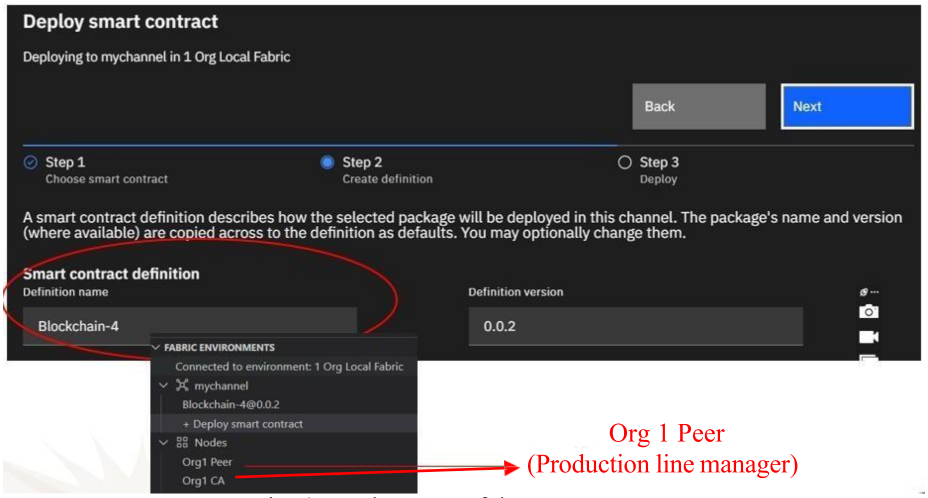

Fig. 4: Deployment of the smart contract

Following smart contract deployment, blockchain transactions were executed in response to wall panel production events. Figure 5 presents the invocation of a smart contract transaction, where a specific 'Wall Panel ID' is submitted as an input parameter. For example, the user submitted 'Wall Panel ID:7' to generate the wall panel information. The submission of this identifier represents the occurrence of a manufacturing event associated with the corresponding wall panel. Upon submission, the transaction is endorsed by peer nodes and committed to the distributed ledger following the defined consensus mechanism. This process demonstrates that physical production events in MCM are translated into blockchain transactions, enabling real-time and tamper-resistant recording of manufacturing activities.

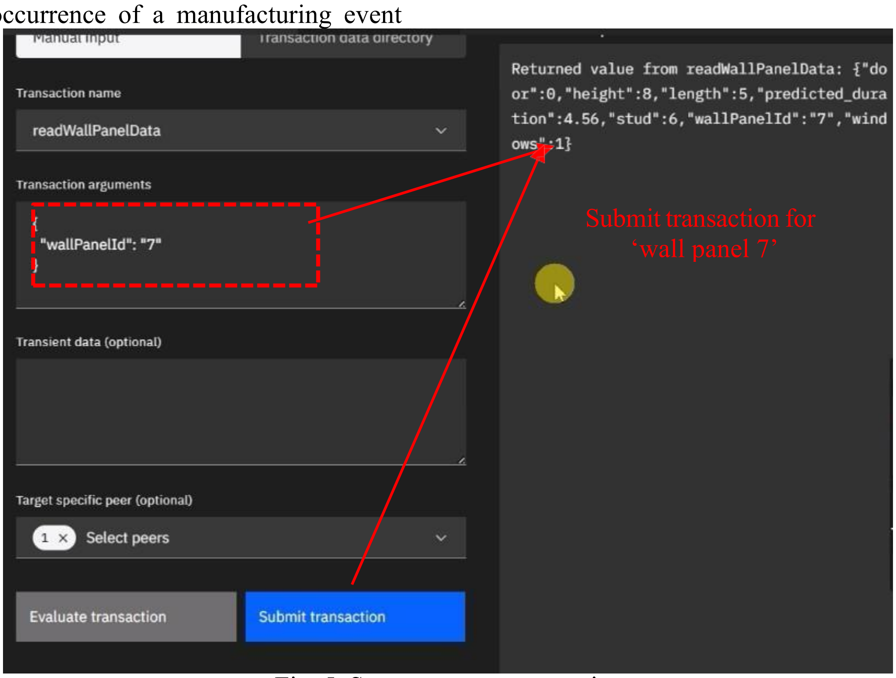

Fig. 5: Smart contract transaction

To ensure data integrity and consistency, manufacturing workflows were formalized within the smart contract logic. Figure 6 shows an excerpt of the implemented smart contract (chaincode) for the case study. The smart contract includes validation mechanisms that verify the existence of wall panel records (e.g., new window value, new height value and new predicted duration) before allowing updates to be committed to the ledger. This logic prevents duplicate entries and enforces predefined business rules governing production data submission. Invalid transactions are automatically rejected, ensuring that only verified manufacturing events are immutably recorded. This implementation confirms that data validation is enforced at the blockchain layer without reliance on centralized control.

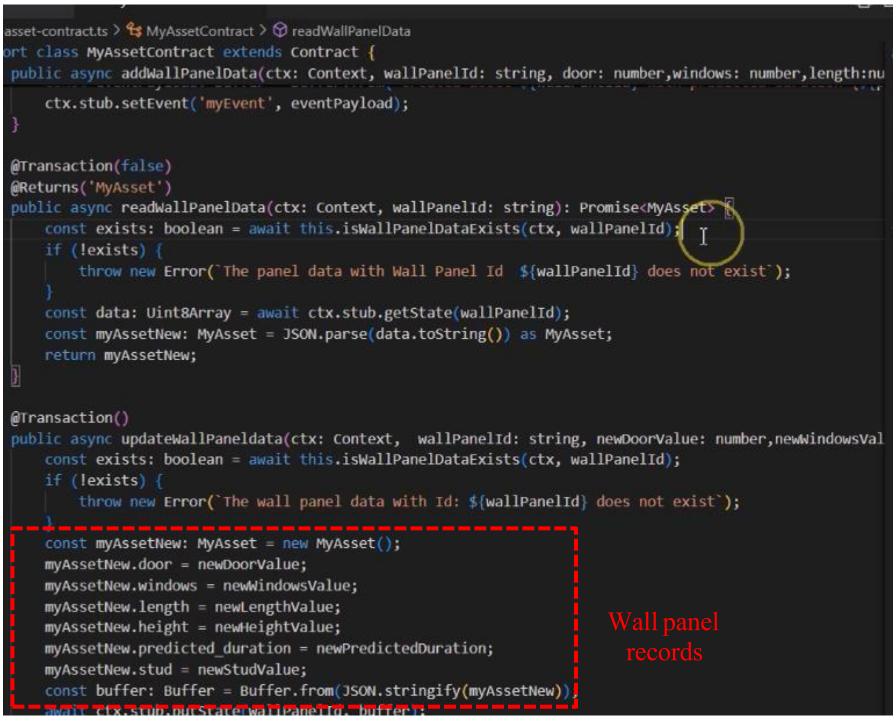

Fig. 6: Implemented smart contract

In addition to transaction execution, this paper evaluated the system's ability to retrieve and verify stored production data. Figure 7 illustrates the execution of a read-only query transaction used to retrieve wall panel production information from the blockchain ledger. For example, the 'wall panel ID 2' has: 3 doors, 11ft height, 12 studs and an estimated process time of 14.12 minutes. The query output confirms that production data recorded during earlier manufacturing events remain persistently stored and accessible in a structured format. Authorized participants can retrieve wall panel status, timestamps, and historical records without modifying ledger contents. This capability demonstrates the traceability, transparency, and immutability of the proposed method, supporting post-event verification and informed decision-making in MCM.

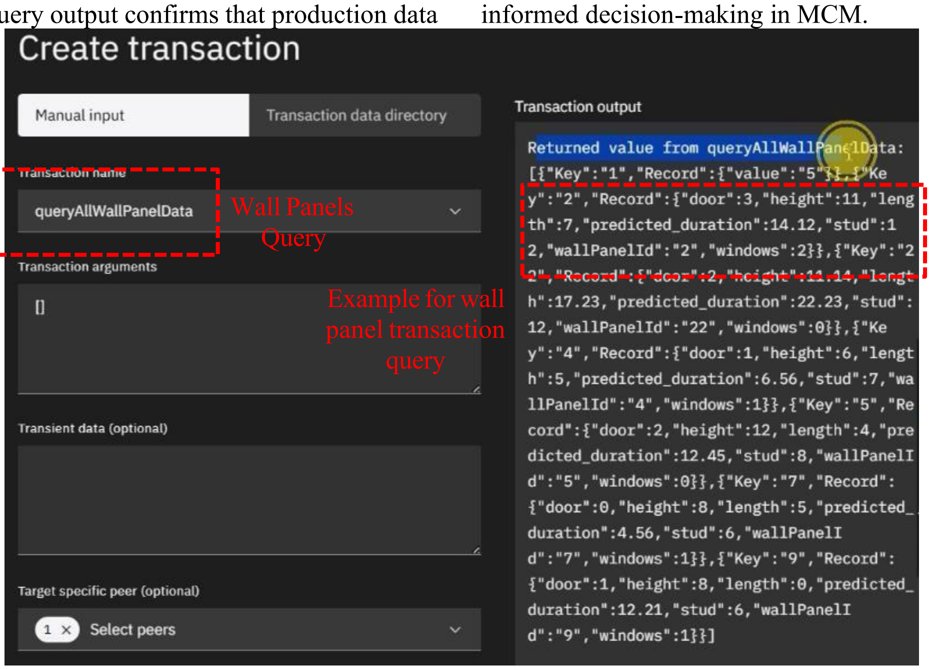

Fig. 7: Execution and query of a transaction

Collectively, this demonstrates the end-to-end application of the proposed method, from smart contract deployment and event-driven transaction execution to validation and data retrieval. The successful implementation enhances data integrity, transparency, and stakeholder trust. In addition, it supports the feasibility of integrating blockchain as a digital infrastructure for managing production information in modular construction.

5 Conclusion and Future Works

This paper presented a newly developed permissioned blockchain-based method using Hyperledger Fabric to enhance data integrity, transparency, and multi-stakeholder coordination (i.e., production line manager and on-site supervisor) in MCM. The method integrates a multi-peer blockchain network, customized smart contracts for managing wall panel production information, and a distributed ledger structure capable of securely recording and synchronizing manufacturing events. Through a case study implementation, the system successfully executed event-driven transactions, enforced smart-contract-based validation rules, and enabled the immutable storage and retrieval of production data. This demonstrates that wall panel information from the production line can be systematically translated into blockchain transactions and subsequently queried for verification and traceability.

However, the implementation involved only two peer organizations (i.e., production line manager and on-site supervisor), which limits the evaluation of scalability and interoperability across a broader modular construction supply chain. Future research should therefore focus on expanding the blockchain network to additional stakeholders and evaluating system performance in full-scale manufacturing environments.

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