Linking permissioned blockchain to Internet of Things (IoT)-BIM platform for off-site production management in modular construction

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Highlights

- A novel blockchain-enabled IoT-BIM platform (BIBP).
- The business process of off-site production in modular construction is reviewed for designing BIBP.
- A novel three-layer system architecture of BIBP.
- The prototype for BIBP was proven for avoiding a single point of failure in IoT networks.
- The prototype for BIBP was proven for ensuring the provenance of BIM modifications.

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Abstract

Traditionally, construction managers were considered more experienced in project management than off-site production management, although the latter is gaining importance with the renaissance of modular construction worldwide. Various Internet of Things (IoT)-enabled Building Information Modelling (BIM) platforms have been developed to facilitate production management by providing better information visibility, traceability, and a more collaborative working environment. Nevertheless, by and large, existing platforms suffer from two shortcomings: (a) the 'single point of failure' problem of IoT networks and (b) how to guarantee the provenance of BIM modifications from multi-sources. This research aims to develop a blockchain-enabled IoT-BIM platform (BIBP) for off-site production management in modular construction (OPM-MC) that can overcome the shortcomings. A design science research method is adopted to develop a three-layer BIBP system architecture. The system architecture is implemented and then compared with the existing IoT-enabled BIM platform. It was found that BIBP can avoid a single point of failure in IoT networks and ensure the provenance of BIM modifications with reduced storage costs in OPM-MC. The system architecture developed in our study can help the industry advance beyond the rhetoric to develop practical blockchain-enabled IoT-BIM applications. Future works are recommended to fine-tune the platform and test and evaluate it in various scenarios.

Keywords: Blockchain, Internet of Things, BIM, Off-site Production Management, Modular Construction

1. Introduction

Modular construction (MC) is a procurement innovation that is fostered from the globalization of construction logistics and supply chain (CLSC). It allows a construction project, traditionally cast in-situ on a congested site, to be designed in one place and manufactured/produced building "modules" in an off-site factory and transporting them to a construction site for installation (Darko et al., 2020). Widely propagated benefits of adopting MC include enhanced cost-effectiveness, productivity (Wuni and Shen, 2020), quality of works (Deng et al., 2017), site safety, sustainability, and reduced construction period and wastage (Lu et al., 2018).

Nevertheless, MC also results in several new non-trivial challenges. Firstly, it is the quality assurance and material authenticity in off-site production. This is particularly onerous as now the production is taking place in a remote, off-site place with many embedded trades. Stakeholders raised concerns about the nonappearance of systematic records of inspection and operations (Li et al., 2021a) or the ones that may suffer input errors, document loss, and even tampering (Zhong et al., 2020). Secondly, it is the fragmented CLSC. The high level of off-site production in an MC project involves various stakeholders with diversified backgrounds, including clients, designers, engineers, suppliers, manufacturers, transporters, contractors, and sub-contractors (Luo et al., 2019). To this end, a high level of coordination and collaboration is much desired. However, it should be noted that many MC projects involve numerous stakeholders who store, retrieve and manage information on their own isolated systems (Li et al., 2019). In Hong Kong, the issue of CLSC fragmentation is amplified when the production work of MC has been completely shifted to the Great Bay Area of Mainland China. These issues hamper higher levels of trust, which is further execrated by the travel restrictions of dispatching authorized persons as inspectors due to COVID-19 outbreaks around the globe.

Scholars and practitioners have been enthusiastic in developing platforms for off-site production management in modular construction (OPM-MC) primarily by adopting Building Information Modeling (BIM) and the Internet of Things (IoT) (Li et al., 2016; Zhong et al., 2017; Xu et al., 2018; Zhou et al., 2021). These IoT-BIM platforms are designed to collect near real-time data to enhance visualization and traceability. Construction stakeholders can then supervise the progress and accumulated costs in practices such as OPM-MC. However, centralized IoT-BIM platforms may bring a "single point of failure (SPOF)" problem. Here a SPOF refers to one component of a system that, if it fails, will make the entire system unable to perform its primary functions (ISO, 2020). For example, noisy and malicious data produced by IoT sensors would affect the trustworthiness of IoT networks (Lu et al., 2021a). It further compromises the integrity of the IoT-BIM platforms. Another example is to modify BIM without providing provenance. The designer may change the window size from 750 mm x 1400 mm to 1400 mm x 1400 mm without notifying all participants, resulting in rework and additional costs. The current IoT-BIM platforms cannot ensure the single point of truth of any modification in BIM (Das et al., 2021). Thus, it leaves room for manipulations of BIM models without traceability (Xue and Lu, 2020). Together, these issues restrain the performance of IoT-BIM platforms for OPM-MC.

Blockchain, used most broadly to record bitcoin and other cryptocurrency transactions, has been actively investigated for its various potentials in construction (Wang et al., 2020; Lu et al., 2021b; Li et al., 2021a). A blockchain refers to a distributed database with cryptography and decentralized consensus mechanisms (Kuhle et al., 2021). Lately, blockchain has also been proposed for IoT and BIM to establish trust in distributed IoT networks (Reyna et al., 2018; Li et al., 2021b) and record the history of BIM changes (Zheng et al., 2019; Xue and Lu, 2020). Theoretically, integrating blockchain with IoT and BIM can eliminate the pain points of the IoT-BIM platforms mentioned above. Nevertheless, configuring a blockchain-enabled IoT-BIM platform (BIBP) for OPM-MC is still in the conceptual stage rather than a developed system. At the current stage, there is a lack of an effective system architecture that uses blockchain to prevent a SPOF of the IoT networks and ensure a single point of truth of BIM modifications.

Thus, this research aims to develop a spanking-new BIBP for OPM-MC. The specific objectives of this research are to: (1) define the objectives of the proposed platform; (2) propose a system architecture of the BIBP based on the defined objectives; (3) substantiate the proposed system architecture by implementing a prototype and evaluate its performance by comparing with existing centralized IoT-BIM platforms. The remainder of this paper is organized as follows. Section 2 introduces the related works of BIM, IoT, blockchain, and their integrations. Section 3 reviews the current business process of OPM-MC. Section 4 presents the research methodology. Section 5 gives the details of the BIBP system architecture. Section 6 shows the developed platform and evaluates its performance. Section 7 offers our discussion, and Section 8 concludes this research.

2. Background

2.1 Building Information Modeling (BIM)

In recent years, the introduction of BIM has been perceived as one of the critical developments in industrialized construction. BIM is a nomenclatural term employed to refer to a series of technologies and associated works utilized to describe and manage information used and produced for the process of designing, constructing, and operating buildings (Xue et al., 2021). The taxonomy of BIM information differentiates geometric, semantic, and topological types (Xue and Lu 2020). Open BIM supports the definition of the above information, and the Industry Foundation Class (IFC) (an open BIM standard) is usually used for data exchange for BIM interoperability.

BIM has been widely adopted in MC in various stages of a project lifecycle, including feasibility study (Li et al., 2020), design (Alwisy et al., 2019), production (Li et al., 2019), transportation (Bortolini et al., 2019), installation (Zhang et al., 2016), and maintenance (Wang and Piao, 2019). However, rare works contribute to BIM security, e.g., BIM modification audit and provenance (Zheng et al., 2019). For instance, the design of modular products in BIM may be modified due to budget or client requirements. The modification of BIM information is usually updated rather than keeping revision history. Even if the modification records are stored, it is difficult to guarantee the integrity of historical information (Xue and Lu, 2020). In addition, the modification records rely on complete trust in the central operator. Once the internal operators misbehave, the tampered information will lead to production rework and even legal proceedings. In short, the main challenge is the lack of an effective way to safely track BIM changes (Das et al., 2021). Therefore, this research aims to link the blockchain with BIM to track off-site production information in modular construction.

2.2 Internet of Things (IoT) and IoT-enabled BIM

IoT can provide accurate and timely information collection (Trappey et al., 2017). Practitioners and scholars have suggested many core components of the IoT, such as RFID (Radio Frequency Identification) tags, NFC (Near Field Communication) tags, and GPS sensors to help realize its concept (Zheng et al., 2018). Besides, Niu et al. (2016) proposed smart construction objects (SCOs), an IoT model with sensing, processing, and communication capabilities, to facilitate the information exchange among construction resources.

To fully achieve the potential of BIM in MC projects requires accurate information collection, timely information exchange, and automatic decision support throughout the project life cycle. Thus, several researchers have developed IoT-enabled BIM platforms for construction safety management (Xu et al., 2018), construction logistics and supply chain management (Zhong et al., 2017), on-site assembly services (Li et al., 2016; Zhou et al., 2021), and facility management (Hu et al., 2016). Tang et al. (2019) summarized five IoT and BIM integration methods: (1) employing the Application Program Interfaces (APIs) of BIM tools' and relational databases; (2) adopting novel data schema to reconstruct BIM data; (3) formulating novel query language; (4) applying semantic web technologies; and (5) adopting a hybrid approach. However, integrating the IoT and BIM cannot guarantee information security (Lu et al., 2021a). For example, the IoT may provide noisy or malicious data to BIM, thereby reducing the trustworthiness of the IoT-enabled BIM platforms. Thus, this study aims to use blockchain to avoid a SPOF in IoT networks.

2.3 Blockchain

Three essential components keep the functioning of a blockchain: cryptography, distributed ledgers, and a consensus mechanism (Xue and Lu et al., 2020). Cryptography (e.g., hashing algorithms) embodies the principles and methods for transforming data to hide their semantic content, restrict their unauthorized use or prevent undetected modification (ISO, 2020). Distributed ledgers involve an accounting technique to record when anything of value is transacted. These ledgers are shared and synchronized among users using a decentralized consensus mechanism (Li et al., 2021a). Consensus mechanisms are procedures used to reach an agreement on the order and correctness of data (ISO, 2020). Besides, blockchains can be configured with smart contracts. Smart contracts are digital contracts that can self-execute processes when preset conditions are satisfied (Kuhle et al., 2021). Some studies classify blockchain platforms as permissioned or permissionless based on whether platforms provide access control on their network. Users are pre-authorized to use a permissioned blockchain platform, such as Hyperledger Fabric.

Only a few studies have explored blockchain in OPM-MC. Cao et al. (2019) demonstrated a blockchain-based system to improve the transparency of information between steel production companies and buyers. Li et al. (2021a) proposed a two-layer blockchain-based model to supervise off-site production in modular construction and protect the privacy of participants. Wang et al. (2020) designed a blockchain-based framework to improve the information sharing of off-site production, transportation, and on-site assembly in precast construction. It is observed that more studies are focused on the use of blockchain to enhance the traceability of the construction supply chain (e.g., Zhang et al., 2016; Zhong et al., 2020) and the overall management of information (Sheng et al., 2020; Lu et al., 2021b). However, the benefits of using blockchain in OPM-MC cannot be cultivated with an incomplete, inaccurate, and untimely data exchange and lack of real-time visibility (Lee et al., 2021). To deal with these challenges, this study aims to link blockchain with IoT-BIM platform for OPM-MC.

2.4 The Integration of Blockchain, IoT, and BIM

Recently, researchers have been studied the integration of blockchain and BIM or the integration of blockchain and IoT separately. For example, Xue and Lu (2020) developed a semantic differential transaction (SDT) approach to lessening information redundancy for blockchain and BIM integration. Zheng et al. (2019) proposed a blockchain-based model called "bcBIM" for BIM modification audit and provenance. Additionally, several studies have found that integrating blockchain and IoT can help immerse trust into IoT-oriented data sources and secure IoT networks (Reyna et al., 2018; Li et al., 2021b). Therefore, previous studies have shown that blockchain has great potential to avoid a SPOF in the IoT networks and ensure the provenance of BIM modifications, which are the two main challenges of the current IoT-BIM platforms. Lee et al. (2021) proposed an integrated IoT-BIM and blockchain framework to support accountable information sharing in construction. Nonetheless, the integration of blockchain and IoT-BIM is still in its infancy.

The research gaps identified can be summarized as follows. Firstly, there is a lack of system architecture to guide the integration of BIM, IoT, and blockchain for specific OPM-MC functions. Secondly, the integrated blockchain-enabled IoT-BIM has not been compared with the current centralized IoT-BIM platform for evaluation. Thus, this research aims to define the objectives of the BIBP for OPM-MC; propose a system architecture of the BIBP based on the defined objectives; substantiate the proposed system architecture, and evaluate its performance.

3. Off-site Production in Modular Construction

The OPM-MC business process generally contains production preparation, production, and inspection. The scope of the OPM-MC process has been identified as follows: (1) this process begins when the contractor's project manager signs the contract to confirm production; (2) the inputs are the production plan and the design drawings; (3) this process ends when project manager confirms the delivery order; and (4) the outputs are the qualified modules. As shown in Figure 1(a), the main contractor works with the manufacturer and designer to propose a production plan after placing an order. After confirming the design drawings, the manufacturer's design department formulates detailed shop drawings. The project client and the contractor need to approve shop drawings when these drawings are ready. After approval, the manufacturer can develop a master production plan. Then, a bill of materials will be formed according to the production execution plan. Next, the manufacturer's procurement department will order materials such as 2D panels from suppliers. The supplied materials will only be utilized after passing inspections and tests. Materials that pass the inspections will be sent to the factory, and then the production department will start production.

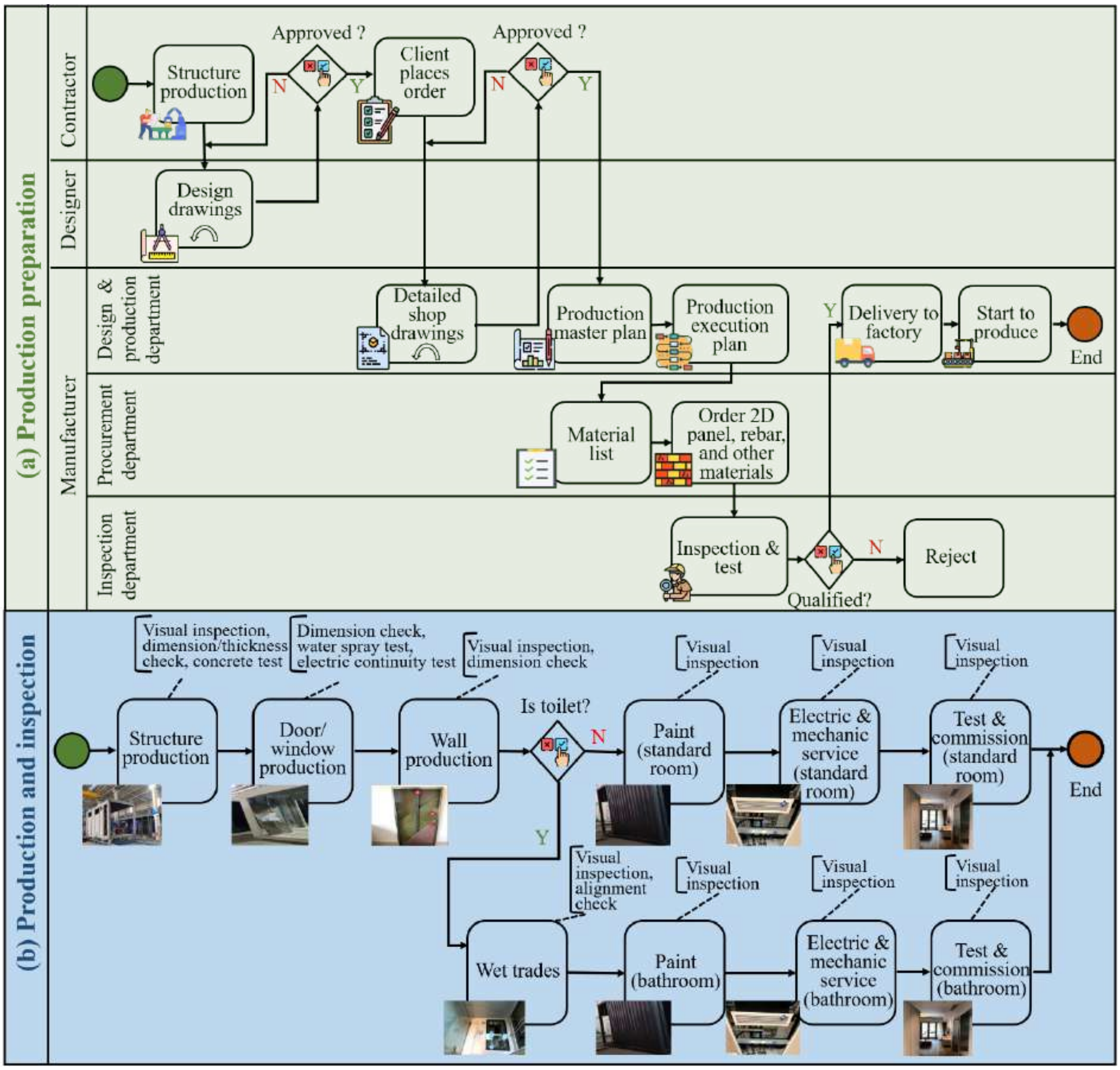


Figure 1. The business process of off-site production in modular construction: (a) production preparation; (b) production and inspection (Adapted from Li et al., (2021a))

Figure 1(b) shows that the standard module is produced through the following five main procedures: structure, door/window, wall, paint, electrical and mechanical services, and testing and commission. Workers need to apply additional wet trades to bathroom modules. For example, they need to add waterproof layers and conduct flood tests. Various inspection and testing means are employed to ensure quality control and assurance at each checkpoint, as shown in Figure 1(b). For example, check the thickness of the fireproof coating on the structural members at the structure stage, and check the dimensions of the windows at the door/window stage.

Several existing information security problems have been observed when applying IoT-enabled BIM platforms in the current business process of OPM-MC. Firstly, the noise data generated by IoT sensors reduces the data quality of BIM and further affects the trustworthiness of the IoT-BIM platform. For instance, the erroneous production status generated by IoT sensors is reflected in BIM, causing decision-makers to make inappropriate decisions in the subsequent transportation preparation stage. Secondly, there is a lack of an effective method to ensure the provenance of BIM modifications. For instance, BIM has been modified in multiple versions due to design change requirements, so the manufacturer had to spend considerable time asking each stakeholder and its departments to provide signatures to confirm that the current version they hold is the "right version".

4. Research Methodology

In this study, the design science research (DSR) approach was adopted to develop a BIBP system architecture for OPM-MC. DSR, as a scientific knowledge production philosophy, seeks to develop innovative constructs to solve real-world problems and simultaneously make prescriptive scientific solutions (Peffers et al., 2007). Our study used four steps, as shown in Figure 2. In the first step, to define the objectives of the BIBP system architecture, the research team visited a prefabrication factory for module production in Foshan, Mainland China, between February and March 2021, understanding the challenges of the existing IoT-BIM platform from the employees. Then, the research team analyzed the knowledge obtained from the site visits in two research workshops in April 2021. In the second step, the research team brainstormed in four meetings in May 2021, synthesizing the knowledge obtained from the literature and defined objectives. This process was non-linear and required multiple iterations to develop a promising solution (some solutions are feasible but not the most promising) for which the system architecture was developed.

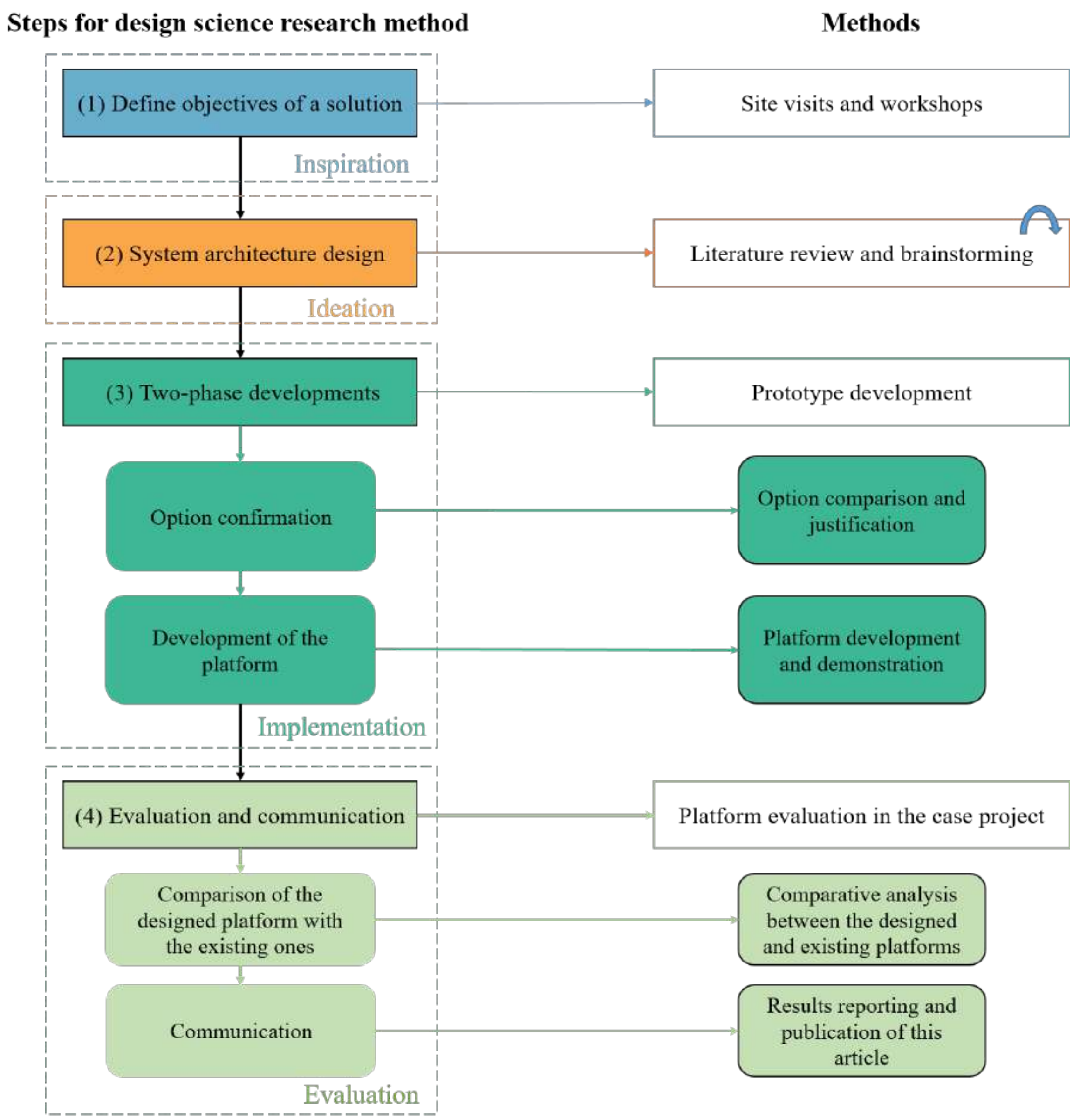


Figure 2. Research methodology

The third step involved a two-phase development of the prototype system. In the first phase, the options of IoT plan and application development language were firstly compared and selected with justifications. RFID has been widely used for production management due to its bright advantages. Through numerous studies (e.g., Poon et al., 2009), RFID has been proven to facilitate data collection and information sharing in production control efficiently. In addition, it can react quickly and flexibly to the dynamic environment of the production chain (Zhong et al., 2015). Compared to other IoT options (e.g., NFC and GPS), RFID technology adoption with component-level tagging, from the research conducted by Bottani and Rizzi (2008), shows that positive revenues for all production stakeholders could be achieved. Thus, passive RFID is adopted as the IoT plan in this study. JavaScript was selected to develop applications as it reduces the time required by other programming languages like Java for compilation (Sheikh, 2016). Its structure is simple for the research team to implement the prototype, and it provides various standard components to create user interfaces.

Additionally, blockchain type, development platform, open blockchain BIM standard extension method, and consensus mechanism were selected to implement the system architecture. Among blockchain types (permissioned and permissionless), permissioned blockchains can provide functions such as authorization and identification audit, meeting business cooperation demands (Lu et al., 2021b). The permissioned blockchain was selected as OPM-MC includes numerous stakeholders, and only approved parties can participate in the network. Next, from among three popular permissioned blockchain platforms, namely R3 Corda, Neo, and Hyperledger Fabric (Lu et al., 2021b), Hyperledger Fabric was adopted as the development platform because it provides developers with numerous security-enhanced alternatives and resources due to its maturity (Li et al., 2021a). The SDT method developed by Xue and Lu (2020) was chosen to extend the open blockchain BIM standard IFC. SDT provides a higher IFC compression ratio (e.g., 791.2 for modular room) to minimize information redundancy compared to existing solutions. In addition, it offers rapid IFC restoration from the chain (complete ifcJSON restoration at 200MB/s). Then, the crash fault tolerance (CFT) consensus was chosen. Compared with open consensuses such as proof of work and proof of stake, CFT can avoid network partitions and is relatively fast compared to Byzantine fault tolerance (Hyperledger Fabric, 2020).

In the second phase, BIBP was implemented according to the designed system architecture. Initially, RFID tags are affixed on material packages, prefabricated components, and prefabricated modules to monitor the process states of OPM-MC. The user interfaces were developed to allow input and inquiry production-related operations. Besides, the IFC standard (ISO 16739-1:2018) was extended by appending a set of properties to the BIM family of the precast components. In addition, the SDT method was introduced to compute the version changes of the BIM over time. Next, the blockchain BIM system was implemented on Hyperledger Fabric (version 1.4), and smart contracts were written through JavaScript. The development environment was in Linux 5.4.0-58-generic-lpae (5.4.0-58.64~18.04.1) (Ubuntu 18.04.1 LTS), and the back-end was implemented using SpringBoot (version 2.4.0) allowing the research team to quickly develop a database management system MySQL. The genesis block of the blockchain BIM system was configured to initialize the CFT consensus mechanism.

In the four step, the developed BIBP was tested in the mock-up production phase of a modular construction project. The evaluation was done through a comparative analysis between BIBP and the existing IoT-BIM platform. In previous studies (e.g., Farzan et al., 2008), comparative analysis has been used to test the effectiveness of various information systems before fine-tuning and further development. The evaluation results were disseminated to audiences in manufacturing and modular construction.

5. Architecture Design of the Blockchain-enabled IoT-BIM Platform

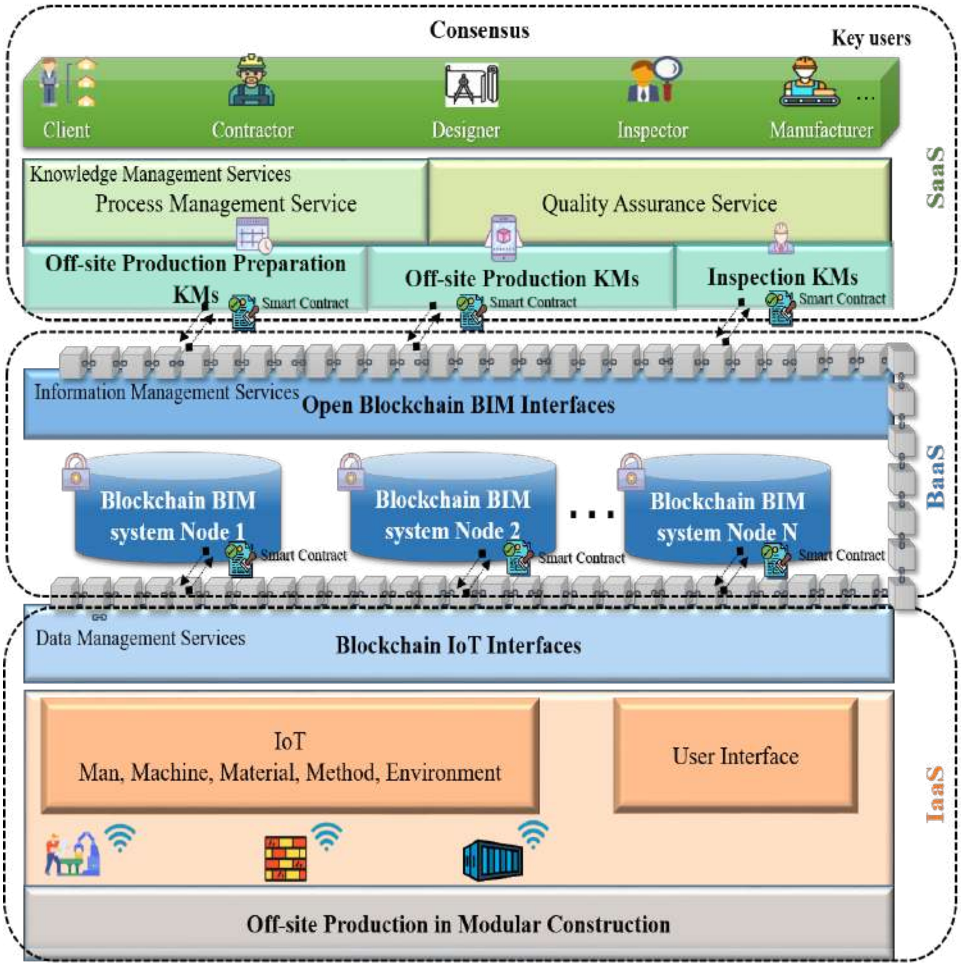
This section describes the architectural structure of the proposed BIBP platform. Section 5.1 illustrates the overall platform development objectives. Section 5.2 offers an overview of the platform. The key components of BIBP are categorized into three dimensions, i.e., Infrastructure as a Service (IaaS), Blockchain BIM as a Service (BaaS), and Software as a Service (SaaS), on data, information, and knowledge aspects, respectively. Section 5.2.1 describes the core components of the IaaS. Section. 5.2.2 introduces the BaaS structure and interfaces. The SaaS Process Management and Quality Assurance (PM/QA) applications are shown in Section 5.2.3.

5.1 Platform Development Objectives

Based on the knowledge obtained from site visits and research workshops, the objectives of the proposed system architecture are defined as follows: (i) it should reinforce the authenticity of the information collected from RFID; (ii) it should record BIM modifications with provenance; (iii) it should provide a foundation for practitioners to develop high-level APIs. APIs developed based on the system architecture should be able to integrate with the existing software in construction.

5.2 Overall System Architecture of the Platform

The platform takes advantage of the XaaS (Anything as a Service) paradigm to bridge the OPM-MC practices and the demands of multiple stakeholders. The whole architecture of BIBP can be divided into three layers from the reality to the OPM-MC demands, as shown in Figure 3(a). The first IaaS layer includes IoT module and user interfaces. The second BaaS layer includes functionality structure to interoperate the information, semantics, and meaningful inferences with existing ERP systems. The third SaaS layer meets the demands of multiple stakeholders with as-needed knowledge-based process management and quality assurance applications. Figure 3(b) summarizes the type, evidence process, media, and external interactions of the three layers. BIBP employs a clear data-information-knowledge (DIK) paradigm to map the evidence from practice to blockchain BIM to users (and existing software systems).



(a) system architecture

ID	XaaS	Evidence process	Media of evidence	External interaction
❶	IaaS	Reality → data	Blockchain system	OPM-MC practice
❷	BaaS	Data → information	Blockchain BIM	Existing ERP systems
❸	SaaS	Information → knowledge	PM/QA on end devices	End users

(b) evidences and external interactions involved in system architecture

Figure 3. Overview of blockchain-enabled IoT-BIM platform

5.2.1 Infrastructure as a Service (IaaS)

IaaS of the BIBP includes two modules, namely IoT and user interface. The edge infrastructure supports the IoT module, which contains IoT-enabled production resources, protocols, gateway nodes, broker nodes, and computing unit nodes. In this study, OPM-MC resources and processes are linked with their virtual twins through RFID, and protocols are used to regulate the synchronization of data-information-knowledge in OPM-MC. Thus, RFID with existing protocols can capture OPM-MC data from regular operations to blockchain BIM. Gateway nodes act as an interface to preprocess the data collected from RFID and feed the data to the subsequent nodes. Broker nodes are responsible for allocating computing unit nodes to handle time-sensitive tasks or transferring challenging tasks to the cloud. By relying on smart contracts, blockchain IoT interfaces can provide users with effective operational control. For instance, once a window is produced for a module, the operator can scan the RFID tag affixed on it and publish this transaction proposal to the blockchain, and when the proposed transaction reaches a consensus in the decentralized network, the smart contract can send a task completion notification to the production manager and other stakeholders. Different combinations of IoT configurations can be provided for various future tasks. For instance, one can use GPS sensors with low energy consumption for future logistics tasks.

The user interface module supports user interaction in the platform. For example, the client can view the inspection results of the material, 2D panels, and 3D modules through the user interface. In addition, the developed user interfaces are connected to a web-based operating platform, allowing users to view the real-time progress of production preparation, production, and inspection through the imported BIM.

5.2.2 Blockchain BIM as a Service (BaaS)

BaaS of the BIBP includes two major modules to interoperate information, semantics, and inferences. The first module is the open blockchain BIM interface, extending the existing open BIM standard IFC (ISO 16739-1:2018). The second module is the blockchain BIM system, which includes BIBP network, ledger, and a set of smart contracts.

The first module (open blockchain BIM standard) is capable of handling more functions than the conventional IFC standard. The new extension involves two parts. The first part is a SDT model for blockchain computability. BIMs are usually massive in size, and the blockchain is not good at handling massive data due to the network capability. In addition, as shared by multiple stakeholders, BIM is subject to simultaneous changes by different parties at the same time. The research conducted by Xue and Lu (2020) shows that SDT can manage real-time, simultaneous changes as IFC change consensuses. The other extension to IFC is the IoT properties, which used to be non-existed in the IFC properties. Examples include production lines, production preparations, and defects. These new properties are attached to the IFC standard directly.

Figure 4 shows an example illustrating how the new open blockchain BIM standard works on an object’s geometry modification in a BIM. A window on a wall (see Figure 4(a)) was changed to a larger width in Figure 4(b). Figure 4(c) shows the corresponding change record, where the two lines indicate the unique identification of the window and the pair of original and changed properties. The changes are associated with the IFC objects by a multi-level decomposition of the building hierarchy. The change record is short – which is not available in IFC without SDT – enough for blockchain. Besides, by swapping the value pair of original and changed properties, the time arrow of the changes can be reversed so that the rewind and tracing operations are available – which are not available in IFC – from the new blockchain BIM standard. With the new blockchain BIM standard, even a massive BIM can be stored on the blockchain.

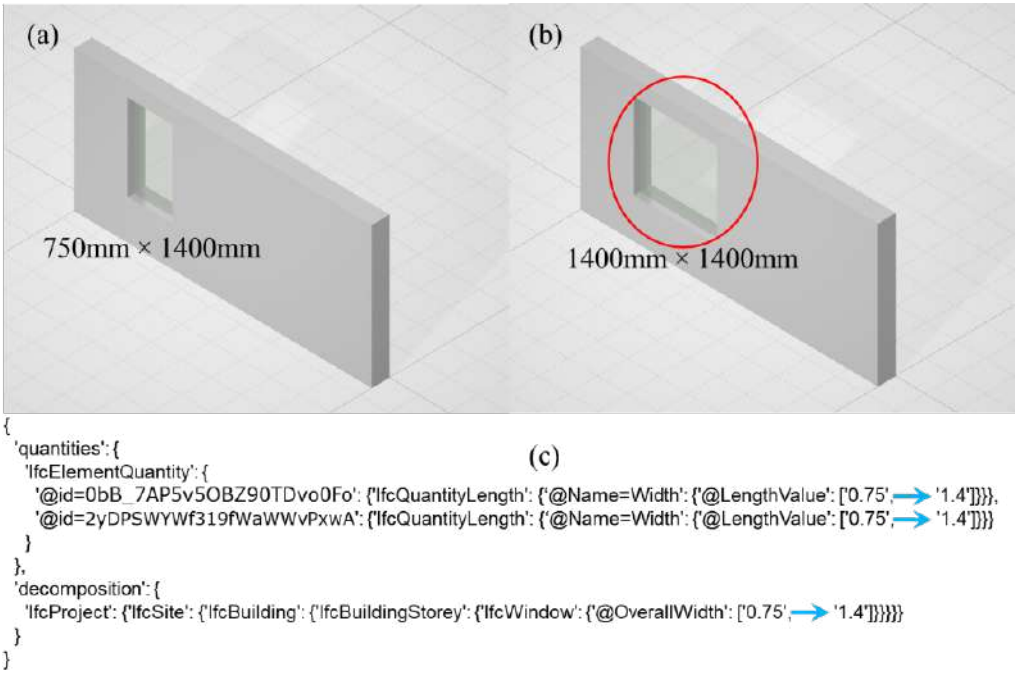


Figure 4. Illustrative example of the semantic differential transaction record of a design change: (a) example wall; (b) window size changed; (c) differential record (0.36KB) of the design change

The second module, blockchain BIM system, is implemented on Hyperledger Fabric (a permissioned blockchain platform), containing the services of the BIBP network, ledger, and chaincode (in Hyperledger Fabric, smart contracts are packaged as chaincode). The details of each service is explained as follows.

(i) BIBP network: The BIBP network is a two-channel structure that provides ledgers (L1, L2) and chaincode (S1, S2) to facilitate data-information-knowledge-driven OPM-MC (see Figure 5(a)). Each dimension (physical space, data space, information space, knowledge space, and service space) of the data-information-knowledge model can serve as an organization (D_{PS}, D_{DS}, D_{IS}, D_{KS}, D_{SS}) to join the network, in which the participants of organizations must obtain certificates from the corresponding certificate authority (CA_{PS}, CA_{DS}, CA_{IS}, CA_{KS}, CA_{SS}). For instance, the certificate authority CA_{SS} can distribute certificates to the client, contractor, manufacturer, and inspector affiliated with D_{SS} to approve their identities. D_{DS} and D_{IS} manage the network by defining policy rules in the network configuration (NC). They also designate members as administration points (O_{IS} and O_{SS}) for ordering services. D_{IS}, D_{KS}, and D_{SS} establish a consortium for knowledge-based OPM-MC services on Channel 1, where configuration CC1 lists involved organizations' definitions and policies. Also, D_{SS}, D_{KS}, and D_{IS} will join peers, named P_{SN} (stakeholder peers), P_{PQN} (process management and quality assurance peers), and P_{BIMN} (BIM peers), to Channel 1. Decentralized applications (DApps) such as A_{SC} (stakeholder communication), A_{IPQ} (intelligent process management and quality assurance), A_{BIM} (BIM application) can be connected to Channel 1 by using certificates from the corresponding CAs. S1 is installed on P_{SN}, P_{PQN}, and P_{BIMN} to process business services, knowledge, and information level transactions from DApps, and then these transactions are packaged into blocks by O_{IS} and O_{SS}. Endorsed transactions will be passed to the peers in Channel 1 and recorded in their immutable ledger copies L1.

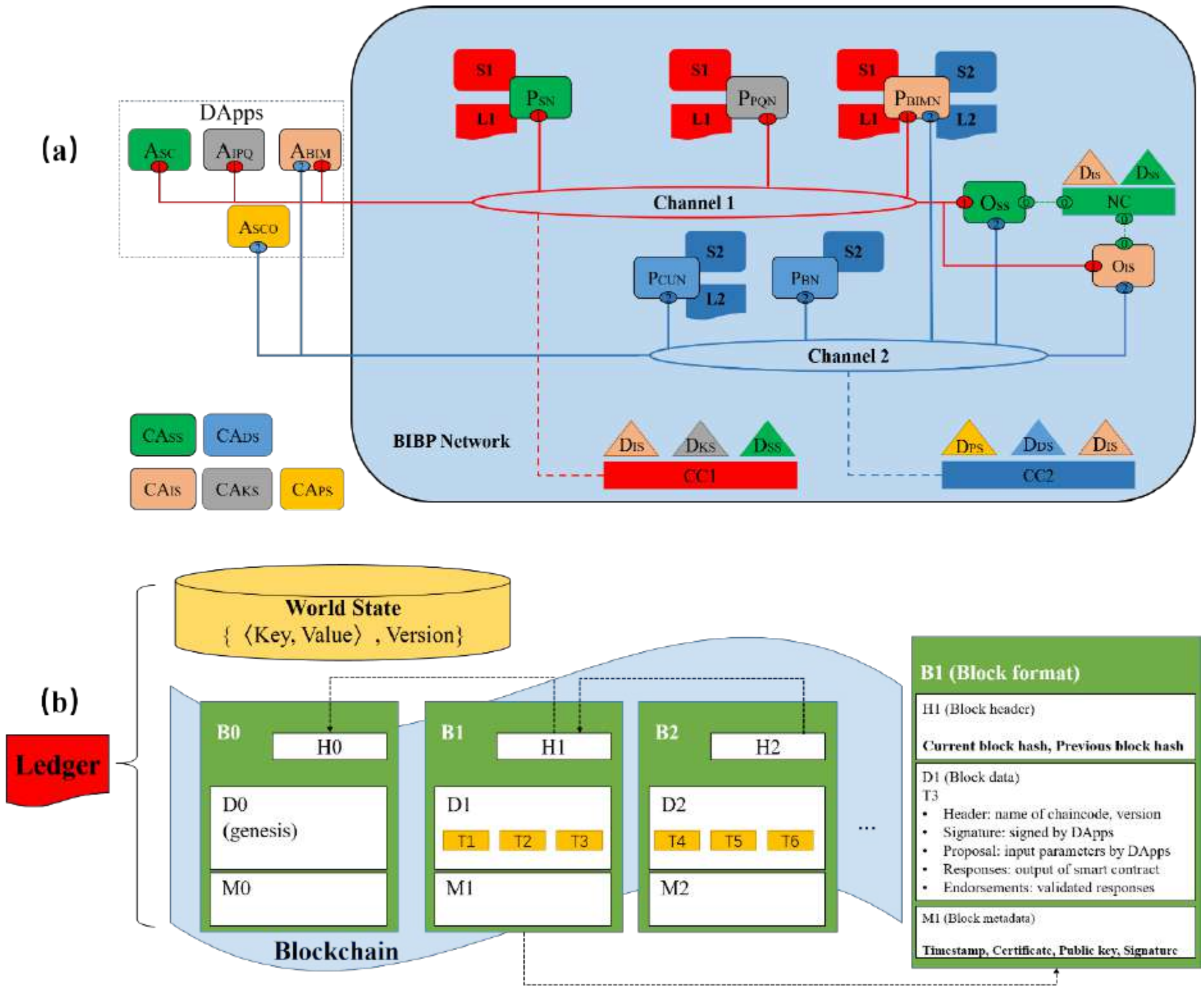


Figure 5. Blockchain BIM system: (a) network; (b) ledger

Similarly, D_{PS}, D_{DS}, and D_{IS} can establish a consortium for data and information-based OPM-MC services on Channel 2. CC2 lists the participated organizations' definitions and policy rules. D_{DS} and D_{IS} will join peers, named P_{BN} (broker nodes), P_{CUN} (computing unit nodes) and P_{BIMN}, to Channel 2. DApps such as A_{BIM} and A_{SCO} (RFID-enabled construction resources) can be connected to Channel 1 by using certificates from the corresponding CAs. S2 is installed on P_{CUN}, P_{BN}, and P_{BIMN} to process data level transactions from DApps, and then these transactions are packaged into blocks by O_{IS} and O_{SS}. Endorsed transactions will be passed to the peers in Channel 2 and recorded in their immutable ledger copies L2.

(ii) Distributed ledgers: In the network, each peer retains a copy of the ledger. The ledger is used to record factual information about OPM-MC objects. For example, in channel 1, BIM-based process management and quality assurance can be recorded on L1, while in channel 2, RFID transactions can be recorded on L2. Each ledger consists of two parts: a world state and a blockchain, as shown in Figure 5(b). The world state shows the current value of an object's attributes as an individual ledger state. The second part, blockchain, is an immutable historical record of how objects arrived at their current states. In a blockchain, blocks are interconnected in sequence, and each block is composed of a block header, block data, and block metadata. A block header includes a block number, a current block hash, and a previous block hash. Block data contains a set of transactions, and each transaction represents a query or update to the world state. When O_{IS} and O_{SS} pack the block in the ordering service, these transactions will be recorded. Block metadata contains a timestamp, certificate, public key, and signature of the block creator.

Two types of world states, namely W1 and W2, are defined in L1 and L2. W1 has three key-value pairs: $\langle K_i^{PM}, V_i^{PM} \rangle$, $\langle K_l^{QA}, V_l^{QA} \rangle$ and $\langle K_m^{BIM}, V_m^{BIM} \rangle$. These key-value pairs show the latest knowledge states of the *i*th project management, *l*th quality assurance and the *m*th BIM changes, respectively. Specifically, K_i^{PM} and K_l^{QA} present the sequence number of OPM-MC processes and inspection procedures. V_i^{PM} and V_l^{QA} show the knowledge of K_i^{PM} and K_l^{QA}, such as project management and quality assurance optimization, simulation and prediction results. K_m^{BIM} indicates the identifier of BIM changes, and V_m^{BIM} shows the properties of BIM changes, such as geometric, semantic, and topological information. The second type of world state W2 $\langle K_j^{SCO}, V_j^{SCO} \rangle$ shows the latest data states of the *j*th SCO. K_j^{SCO} presents the identity of IoT-enabled construction resources, and V_j^{SCO} shows the detailed data about resources, such as states and location. Simply put, every endorsed transaction will cause the key-value pair to change, which is then updated in ledgers.

(iii) Chaincode: In BaaS, chaincode S1 and S2 are installed on the peers in Channel 1 and 2, respectively. S1 contains seven smart contracts for value assessment, capacity assessment, availability assessment, process optimization, quality control, BIM modification, and decision support. When a stakeholder proposes a transaction, the value assessment contract, capacity assessment contract, and availability assessment contract will help evaluate the transaction's business value and the capacity and availability of off-site production resources and processes. Next, these smart contracts will determine whether to validate the transaction based on peers' responses. After approval, A_{IPQ} creates a proposal to Channel 1, in which the process optimization contract and the quality control contract first use the knowledge model to optimize and simulate the proposal and then provide a suitable plan. Then, A_{BIM} can use the BIM modification contract to record the BIM modifications caused by the transaction. When consensus is reached, the optimized process management and quality assurance plan can be imported from BIM to Channel 2 by executing the decision support contract.

Chaincode S2 contains four smart contracts for managing data-oriented services across physical, data, and information spaces. These contracts are state validation contract, state computing contract, state evaluation contract, and state update contract. In DApps, A_{SCO} observes the states of production resources and processes to comprehend the interference in existing process management and quality assurance. Also, these states can be submitted as transaction proposals to Channel 2. When having a new proposal, state validation contract, state computing contract, state evaluation contract can check, compute, and evaluate the data in the proposal, and if they all produce a positive response, the states will be approved. In the process management and quality assurance, the state update contract can give the updated states to the A_{BIM}. Additionally, A_{BIM} can subscribe to past states and interferences to study the performance of process management and quality assurance, thereby improving future performance through knowledge models.

5.2.3 Software as a Service (SaaS)

SaaS of BIBP includes a consensus mechanism. The consensus mechanism adopted by O_{IS} and O_{SS} can help peers ensure the correctness and order of transactions. BIBP uses CFT consensus mechanism to control the transaction flow. In BIBP, A_{SC}, A_{IPQ}, A_{BIM}, and A_{SCO} are the specific services to perform consensus transaction flow.

Users can first use A_{SC} to propose a transaction T1 with proposal P (e.g., the transaction details) to initiate production communication, as shown in Figure 6(a). Then, A_{SC} should invoke the certificate from the CA to verify its identity and authority to join channel 1 through the gateway. Next, A_{SC} sends P to the peers involved in channel 1 for initial endorsement. In this case, P_{SN} assesses the business value of P by using the value assessment contract in S1, provides a response R1, and offers an endorsement E1 with a digital signature. P_{PQN} and P_{BIMN} evaluate the state, capacity, and availability of processes and resources using the capacity assessment contract, availability assessment contract, and BIM. After evaluation, P_{PQN} and P_{BIMN} provide R2 and E2 and R3 and E3, respectively. As a result, A_{SC} receives all the responses and decides whether to proceed further or terminate T1. After reaching a consensus, O_{IS} and O_{SS} can order T1 into a block and deliver it to the peers involved in channel 1. The peers can endorse the block and append the block to the L1 after their endorsement is positive. Then, peers will notify the user of the DApps that T1 has been executed. Afterward, A_{IPQ} uses the transaction that has been ordered and notified to A_{SC} to make an initial plan as transaction T2 with proposal P and send it to P_{SN}, P_{PQN}, and P_{BIMN}. Considering constraints, risks, and uncertainties, P_{SN}, P_{PQN}, and P_{BIMN} simulate and optimize the plan by calling the process optimization contract and quality control contract, and then provide R1 and E1, R2 and E2, R3 and E3. A_{BIM} records the BIM modification caused by the plan as transaction T3 with proposal P and sends it to P_{SN}, P_{PQN}, and P_{BIMN} for endorsement. P_{PQN} and P_{BIMN} will invoke the BIM update contract to review BIM changes and IFC objects and then provide R2 and E2 and R3 and E3. Using the decision support contract, P_{SN} can endorse the modified BIM through a consensus and provide R1 and E1.

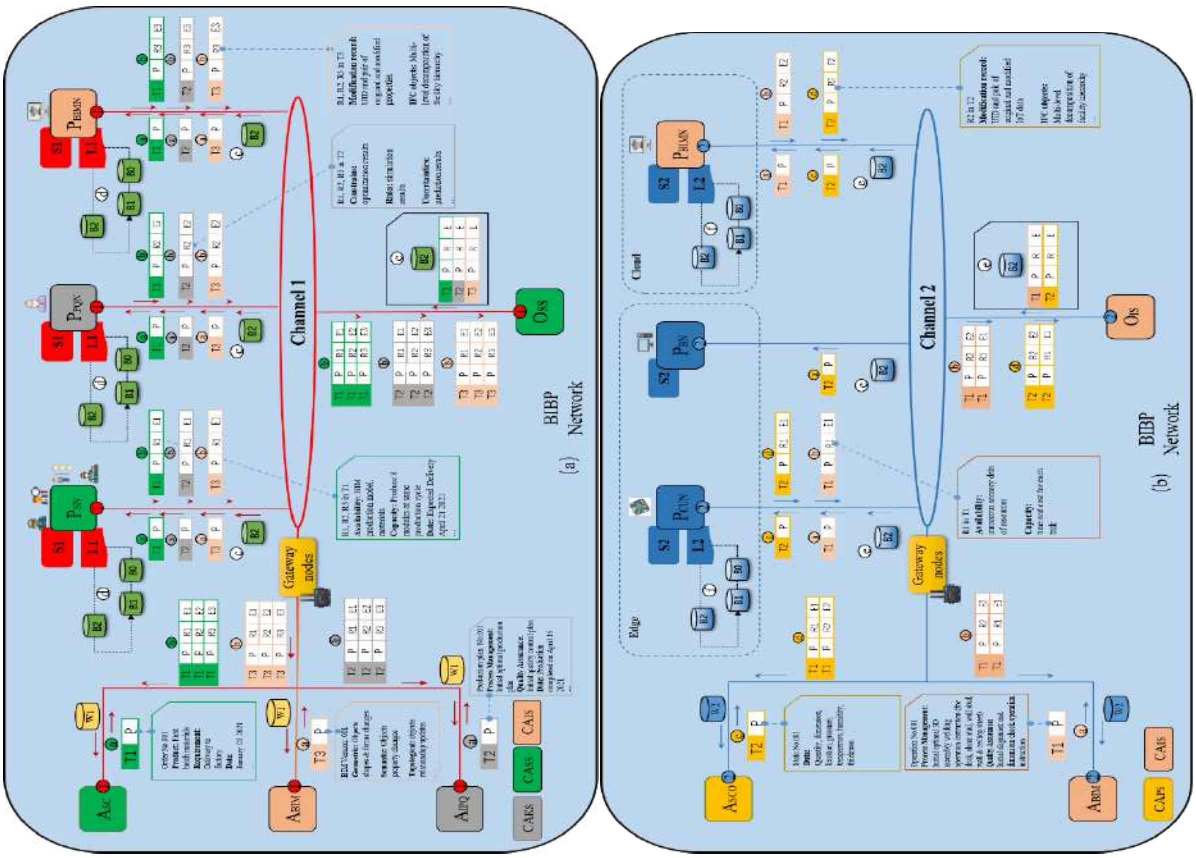


Figure 6. Transaction flows in blockchain-enabled IoT-BIM platform: (a) channel 1; (b) channel 2

The transaction flow of OPM-CM process management and quality assurance in channel 2 is demonstrated in Figure 6(b). After generating T2 in channel 1, A_{BIM} can conduct cross-channel communications and convert the optimal plan into actual operations in channel 2 (as

T1 and P) to guide production process management and quality assurance operations in physical space. The state computing contract and state evaluation contract will be invoked to help P_{CUN} and P_{BIMN} investigate operations while considering the states of production resources and processes. Besides, A_{SCO} can submit the real-time states as T2 and P to P_{BN}. P_{BN} can judge whether there is an abnormality in T2 through the state validation contract. If there is an abnormality in R1, P_{BN} will use the state update contract to help pass the state to P_{BIMN} for further analysis through the knowledge model and provide R2 and E2. On the contrary, if no abnormality is detected, P_{BN} will use the state computing contract to pass the state to P_{CUN} for processing, and provide R1 and E1. In addition, A_{BIM} can subscribe to the states submitted by A_{SCO} to evaluate the existing states and improve future performance by using the state evaluation contract with learning and predictive capabilities. Similarly, O_{IS} and O_{SS} order the transactions into a new block and append it to L2.

6. Implementation and Evaluation

6.1 Implementation

Based on the proposed system architecture, a BIBP is developed as a shadow platform parallel to the existing platform to illustrate its advantages. The research team chose the off-site mock-up production (OMP) phase of a modular construction project as the pilot scenario for developing and implementing the platform.

6.1.1 IoT Module and User Interface for the IaaS Layer

Firstly, the IoT module and user interfaces are implemented for the IaaS layer of BIBP. In this study, passive RFID is adopted as the IoT plan, and RFID tags are affixed on material packages, prefabricated components, and prefinished modules to monitor the process states of OPM-MC, as shown in Figure 7. The set of comprehensive protocols fulfills the need for mapping and integrating the data in existing means and systems to the BIBP. Also, broker nodes are configured to allocate computing unit nodes to handle time-sensitive tasks or transfer challenging tasks to the cloud. Besides, the gateway nodes act as a data converter in the factory. Thus, the RFID actions are captured by A_{SCO}, computed by the computing unit node, endorsed by the peers in channel 2, and recorded on L2.

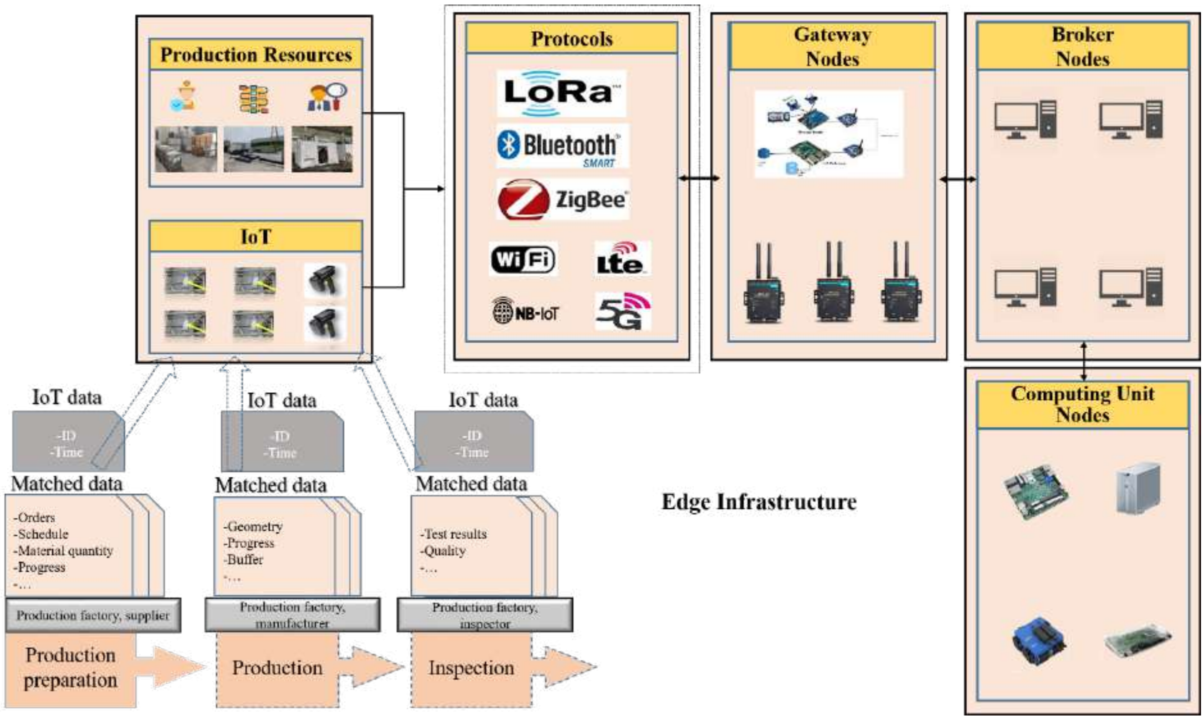


Figure 7. IoT module

The user interfaces are created through the development of the front-end. Figure 8(a) shows the client's interface for inquiring about past transactions. For example, the client can click "Details" to view the inspection results of transactions. By clicking the "View" button, one can also view the real-time off-site production progress in the web-based operating platform through the imported BIM, as shown in Figure 8(b). The buffer capacity of the holding yard can also be viewed in BIM. Such visualization helps project stakeholders identify any delays in OPM-MC to understand the current situation and make relevant decisions collaboratively on BIBP.

Figure 8. BIBP user interfaces: (a) project client's interface for inquiring about past transactions; (b) function for production progress visualization

6.1.2 Open Blockchain BIM Interface and Blockchain BIM System for the BaaS Layer

Secondly, the open blockchain BIM interface and blockchain BIM system are implemented for the BaaS layer. To develop the open blockchain BIM interface, the existing open BIM standard IFC needs to be extended. Thus, an SDT model for blockchain computability is included to bridge the fundamental gap between the IFC and blockchain. The SDT model, as shown in Figure 9(a), can manage the real-time, simultaneous changes as IFC change consensuses. The other extension to IFC is the IoT properties, as shown in Figure 9(b). The extended standard can handle more functions than the original IFC standard. For example, with the schematic definitions in the IFC standard, production analyses can be utilized, such as code checking, progress analysis, and cost estimation.

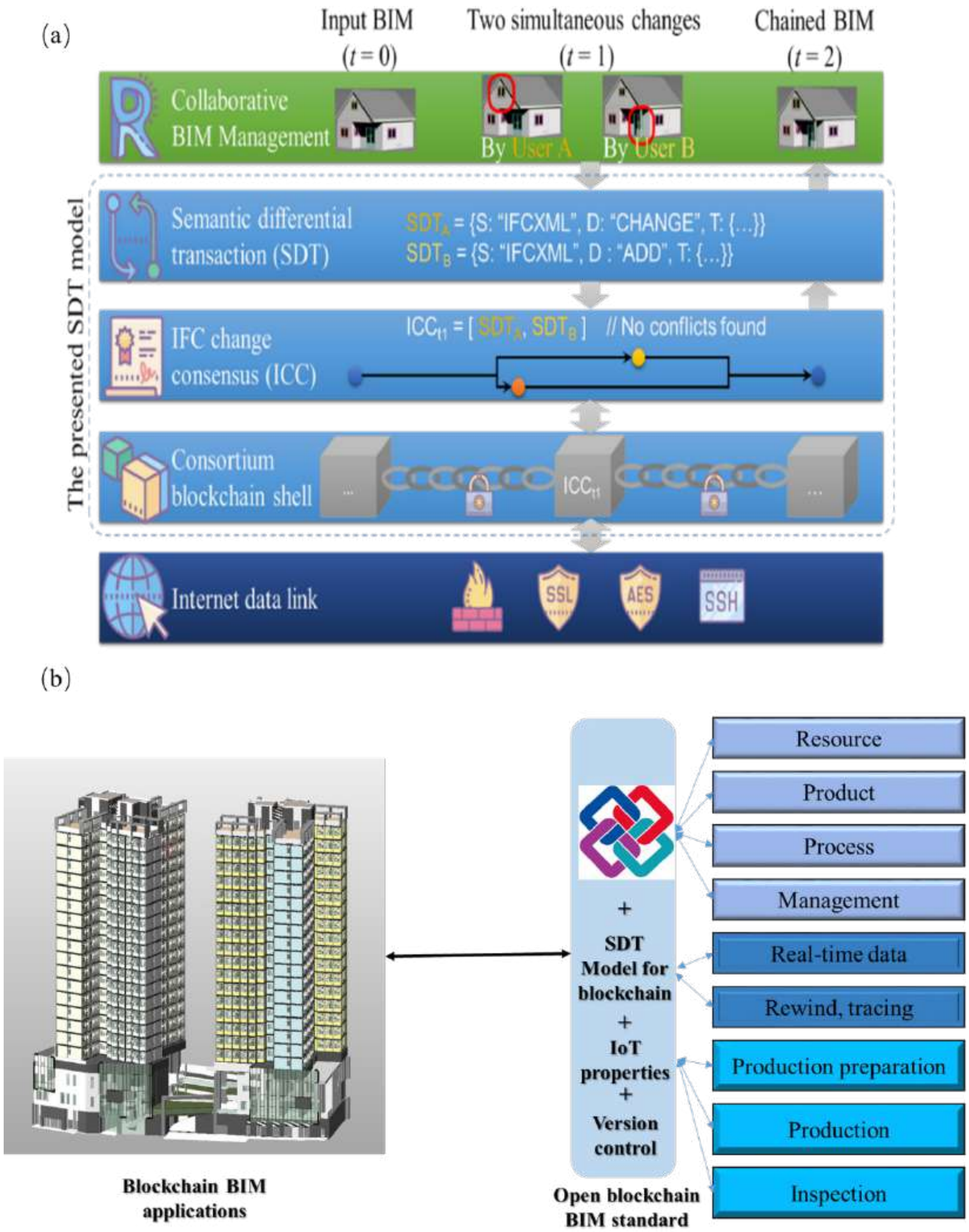
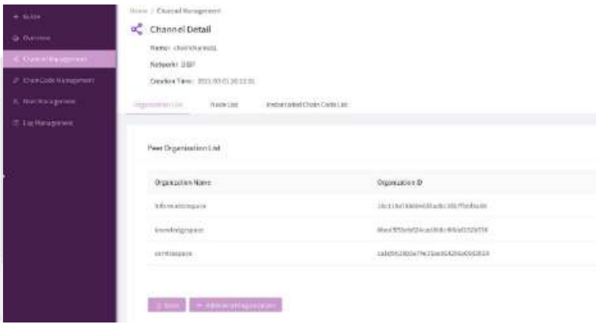


Figure 9. New open blockchain BIM standard: (a) semantic differential transaction model for blockchain BIM; (b) extension of IFC standard (ISO 16739-1:2018)

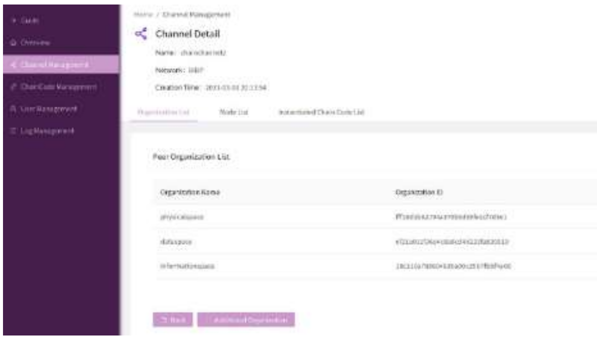
The blockchain BIM system was configured with a network and two sets of chaincode. Moreover, Channel 1 and 2 were configured for passing transactions related to OPM-MC applications to distributed ledgers. Figure 10(a) shows the detailed information of the BIBP network, which includes five-dimension organizations ($D_{PS}, D_{DS}, D_{IS}, D_{KS}, D_{SS}$), where D_{SS}

and D_{IS} also designate members as administration points (O_{IS} and O_{SS}) for ordering services. Additionally, Figure 10(b) and (c) present channel 1 and 2 and their associated organizations, respectively. Three peers (P_{SN}, P_{PQN}, and P_{BIMN}) were added to channel 1 of the BIBP network for intelligent process management and quality assurance in OPM-MC. P_{SN} comprises four peer nodes: client, main contractor, manufacturer, and inspector, while P_{PQN}, and P_{BIMN} each has a peer node. Chaincode (S1) was installed on P_{SN}, P_{PQN}, and P_{BIMN} in channel 1 (see Figure 10 (d)). Similarly, P_{BIMN}, P_{BN} and P_{CUN} joined channel 2 to support state monitoring and operations of process management and quality assurance in OPM-MC, and each of them has one peer node. P_{BIMN} was defined for cross-channel communications between channel 1 and 2. Chaincode S2 was installed on P_{BIMN}, P_{BN} and P_{CUN} in Channel 2.

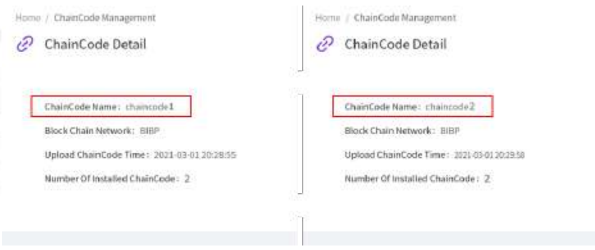
(a) network



(b) channel 1



(c) channel 2



(d) Chaincode

Figure 10. Blockchain BIM system

6.1.3 Consensus Service for the SaaS Layer

Thirdly, the genesis block of the BIBP network was configured to initialize the CFT consensus mechanism for the SaaS layer, as shown in Figure 11. SaaS supports a pluggable consensus mechanism that enables the platform to be more effectively customized to fit particular use cases and trust models. For instance, a more traditional byzantine fault tolerant consensus can be configured in a multi-party, decentralized use case.

```yaml
Orderer:
  Addresses: &ref_1
    - 'ordeross-oss:30000'
    - 'orderois-ois:30001'
  BatchSize: &ref_2
    AbsoluteMaxBytes: 98 MB
    MaxMessageCount: 100
    PreferredMaxBytes: 8192 KB
  BatchTimeout: 2s
  EtcdRaft:
    Consenters: &ref_3
      - ClientTLSCert: >-
          crypto-config/ordererOrganizations/oss.org/orderers/ordeross.oss.org/tls/server.crt
        Host: ordeross-oss
        Port: '30000'
        ServerTLSCert: >-
          crypto-config/ordererOrganizations/oss.org/orderers/ordeross.oss.org/tls/server.crt
      - ClientTLSCert: >-
          crypto-config/ordererOrganizations/ois.org/orderers/orderois.ois.org/tls/server.crt
        Host: orderois-ois
        Port: '30001'The server did not create or modify data.
        ServerTLSCert: >-
          crypto-config/ordererOrganizations/ois.org/orderers/orderois.ois.org/tls/server.crt
    Options: &ref_4
      ElectionTick: 10
      HeartbeatTick: 1
      MaxInflightBlocks: 5
      SnapshotIntervalSize: 20 MB
      TickInterval: 600ms
  OrdererType: etcdraft
  Organizations: null
```


Figure 11. Initialization of the consensus mechanism

6.2 Evaluation

BIBP was tested in the OMP phase of a modular construction project, which involves the production of 10 modules in Foshan, Mainland China. The research team observed and recorded the usage and later compared BIBP with the existing IoT-enabled BIM system developed by Li et al. (2018).

6.2.1 Testing Scenario

The processes for testing with BIBP include production preparation, production, and inspection, as shown in Figure 12. The test involves several typical scenarios, such as order placement, IoT sensing, smart process management, quality assurance, and BIM state updates. The transaction flow of each application scenario is described as follows. Firstly, users can submit the transactions with the proposals from the DApps to peers through the gateway node, and then peers can endorse them by invoking smart contracts and provide corresponding responses. Secondly, peers send the endorsements and responses together with their digital signatures back to the DApps. Thirdly, endorsed and valid transactions are bundled into blocks through the ordering nodes and sent to peers through the defined communication channels. Finally, peers verify the transactions in the newly received blocks, and if these transactions are correct, they append the blocks to their ledgers and send completion notifications to the DApps.

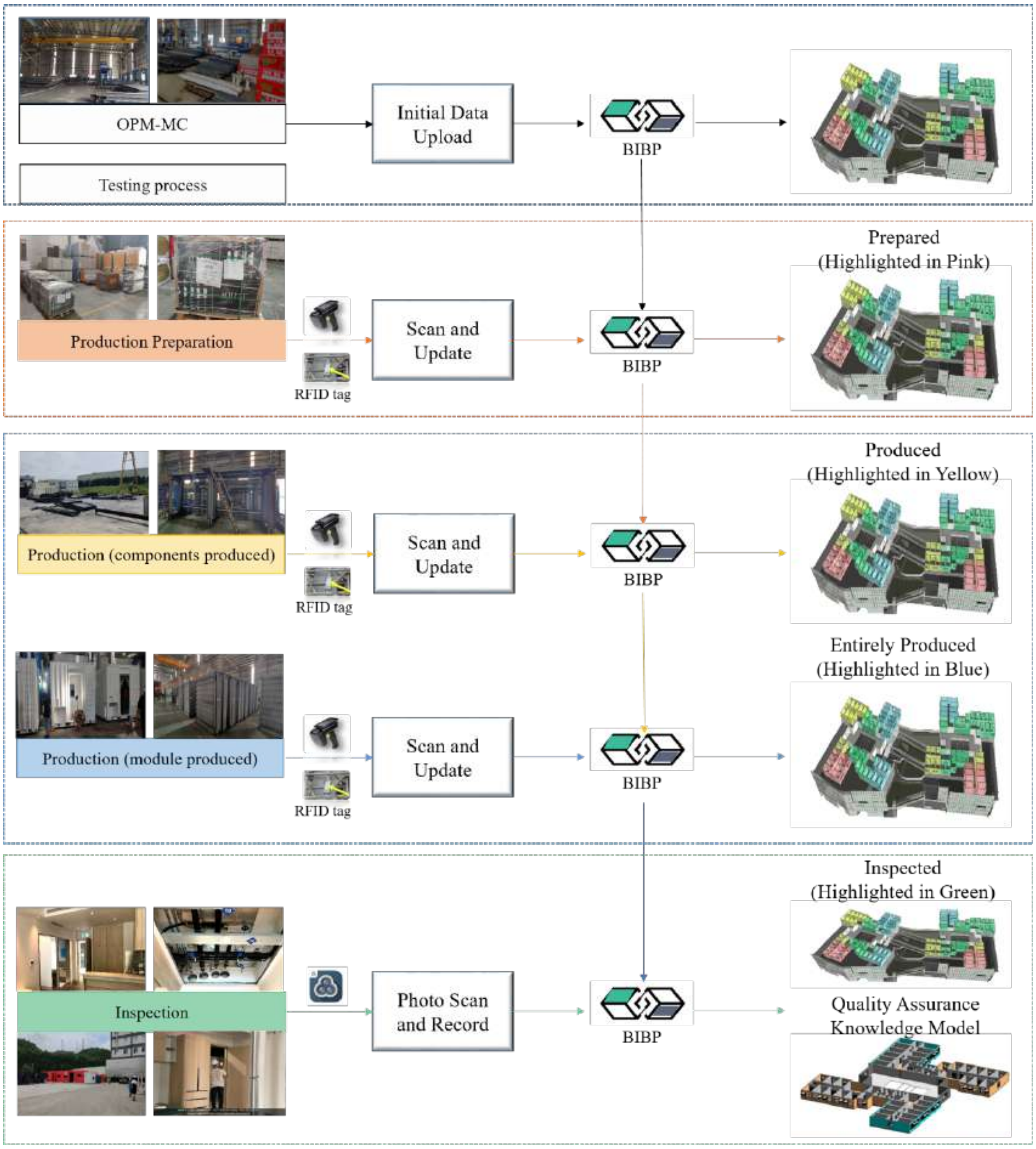


Figure 12. Processes for testing with blockchain-enabled IoT-BIM platform

As shown in Figure 12, the endorsed processes are displayed in four colors through A_{BIM}: (i) pink (production prepared); (ii) yellow (prefabricated components produced); (iii) blue (prefinished modules entirely produced); (iv) green (modules inspected). State changes in BIM (e.g., format: {‘ifcprocess’:{‘entirely produced’→ ‘inspected’}}) can be communicated in channel 1. Besides, when modules are entirely produced, the differences between the as-manufactured BIM and the as-designed BIM can be determined by the knowledge model used for quality assurance in A_{IPQ}.

6.2.2 Evaluation Results

BIBP was evaluated by comparing with the existing IoT-enabled BIM system through five performance indicators: storage cost, security, integrity, authentication, and authorization. There are four settings made: (1) three batches of materials (structure, architecture, MEP) are delivered to the factory; (2) an average of 4 transactions (one order from A_{SC}, one PM-QA operation in A_{IPQ}, one state update in A_{BIM}, one data collection by A_{SCO}) are produced per material batch; (3) a total of 10 modules are produced and inspected in 35 days; (4) an average of 21 transactions (one order from A_{SC}, six PM-QA operations in A_{IPQ}, seven state updates in A_{BIM}, seven data collections by A_{SCO}) are produced per module. A new block is generated every 24 hours to record OPM-MC transactions. Therefore, each block bundles about 7 transactions.

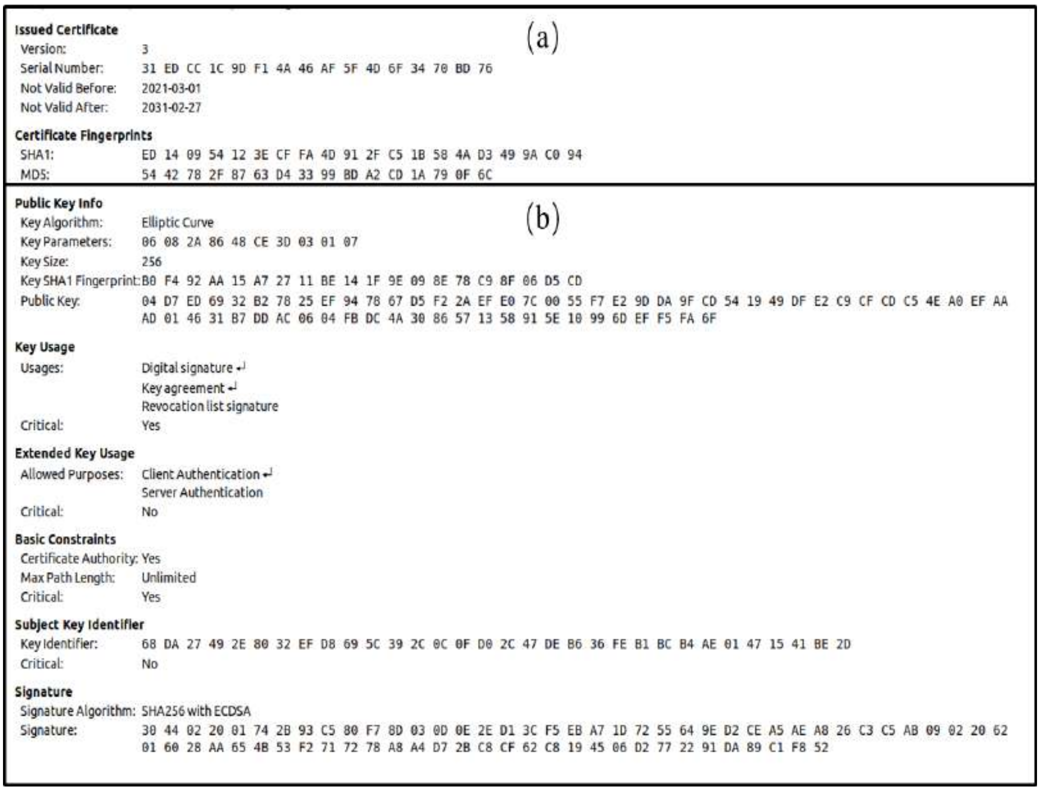
(1) Storage Cost: To ensure the single point of truth for BIM, the BIM model needs to be saved in the blockchain. However, it may lead to information redundancy in the blockchain network. Thus, the storage cost was evaluated for this contribution. In this study, any BIM state change is calculated as the minimum SDT in BIBP, thereby reducing the average size of each transaction to 1 KB (Xue and Lu, 2020) and storing the detailed information in the local database. The total occurred transactions during the test are 222 ($4 \times 3 + 21 \times 10$), and at the maximum, 222 KB (222×1) may be produced in each ledger. In the IoT-enabled BIM platform developed by Li et al. (2018), the BIM model (e.g., the model in Figure 9) is stored in a webserver with the size of approximately 129 MB. Thus, BIBP system architecture can lessen storage load, especially when critical data needs to be tracked in large BIM files.

(2) Security: Another critical design philosophy in BIBP is to avoid a SPOF in IoT networks. To this end, an evaluation was conducted to prove the security of BIBP in screening malicious data. Before the final inspection, the research team deliberately set three of the ten RFID tags as malicious tags (e.g., production completion as incompletion). The results prove that BIBP can avoid a SPOF by rejecting the malicious IoT data through the consensus mechanism. In the same situation, the inspector may directly read the RFID data and input it directly into the IoT-enabled BIM platform, so that the malicious data is not easy to be detected. According to Lu et al. (2021a), the security analysis of BIBP (particularly the IoT network) can also be discussed through integrity, authentication, and authorization.

(3) Integrity: In BIBP, the integrity of IoT data transaction can be ensured when it is exchanged in Channels 1 and 2, because the hash algorithm of the blockchain can make them tamper-proof. In contrast, IoT data collected for the IoT-BIM platform may be manipulated by operators.

(4) Authorization: BIBP uses a permissioned blockchain structure to provide pre-authorized users with certificates to join the network through membership services (see Figure 13(a)). The existing IoT-BIM platform also requires user registration and right permission.

(5) Authentication: In BIBP, the authentication mechanism is realized through digital signatures, which requires each peer to hold two keys (see Figure 13(b)). The public key is used publicly and serve as identity verification anchor, and the private key is used to digitally sign IoT data transactions. On the contrary, due to the lack of such a mechanism, authentication cannot be guaranteed in the existing IoT-BIM platform.


(a)

Issued Certificate
Version: 3
Serial Number: 31 ED CC 1C 9D F1 4A 46 AF 5F 4D 6F 34 70 BD 76
Not Valid Before: 2021-03-01
Not Valid After: 2031-02-27

Certificate Fingerprints
SHA1: ED 14 09 54 12 3E CF FA 4D 91 2F C5 1B 58 4A D3 49 9A C0 94
MD5: 54 42 78 2F 87 63 D4 33 99 BD A2 CD 1A 79 0F 6C

(b)

Public Key Info
Key Algorithm: Elliptic Curve
Key Parameters: 06 08 2A 86 48 CE 3D 03 01 07
Key Size: 256
Key SHA1 Fingerprint: B0 F4 92 AA 15 A7 27 11 BE 14 1F 9E 09 8E 78 C9 8F 06 D5 CD
Public Key: 04 D7 ED 69 32 B2 78 25 EF 94 78 67 D5 F2 2A EF E0 7C 00 55 F7 E2 9D DA 9F CD 54 19 49 DF E2 C9 CF CD C5 4E A0 EF AA AD 01 46 31 B7 DD AC 06 04 FB DC 4A 30 86 57 13 58 91 5E 10 99 6D EF F5 FA 6F

Key Usage
Usages: Digital signature ↵
Key agreement ↵
Revocation list signature
Critical: Yes

Extended Key Usage
Allowed Purposes: Client Authentication ↵
Server Authentication
Critical: No

Basic Constraints
Certificate Authority: Yes
Max Path Length: Unlimited
Critical: Yes

Subject Key Identifier
Key Identifier: 68 DA 27 49 2E 80 32 EF D8 69 5C 39 2C 0C 0F D0 2C 47 DE B6 36 FE B1 BC B4 AE 01 47 15 41 BE 2D
Critical: No

Signature
Signature Algorithm: SHA256 with ECDSA
Signature: 30 44 02 20 01 74 2B 93 C5 80 F7 8D 03 0D 0E 2E D1 3C F5 EB A7 1D 72 55 64 9E D2 CE A5 AE A8 26 C3 C5 AB 09 02 20 62 01 60 28 AA 65 4B 53 F2 71 72 78 A8 A4 D7 2B C8 CF 62 C8 19 45 06 D2 77 22 91 DA 89 C1 F8 52

Figure 13. Authorization and authentication in blockchain-enabled IoT-BIM platform: (a) certificate; (b) digital signature

7. Discussion

This study makes three novel contributions to the existing body of knowledge. Firstly, our research uses the advantages of blockchain to avoid a SPOF in IoT networks. The system architecture lays the foundation for researchers to explore the IoT as blockchain oracles (middleware agents that can capture and verify real-world information and feed it to the blockchain) in construction supply chain management. Secondly, compared with the existing IoT-BIM platform, this research proposes blockchain IoT-BIM as the infrastructure which builds on a new open blockchain BIM standard extended from IFC. The novel open blockchain BIM standard provides a valuable reference for researchers to attach new IoT attributes to BIBP to implement various functions easily. In practice, the new standard is also conducive to public institutions (e.g., governmental supervision units that are unwilling to force commercial software) to access and audit BIMs developed on commercial platforms. Thirdly, our research links the permissioned blockchain to the IoT-BIM platform, which can inherit the advantage of traceability of blockchain to record BIM modifications. The information recorded in a blockchain is reduced mainly by capturing BIM modifications instead of entire BIM files. In our OPM-MC pilot tests, the version history of BIM modifications was captured and placed in a blockchain ledger with only around 222 KB, adequately addressing the challenge of information redundancy in BIM and blockchain integration.

The limitations of this study provide opportunities for future research. Firstly, the algorithm for the SDT model was still slow to process large BIMs, e.g., the 129 MB IFCXML case would exceed the one-hour time limit. Future work can develop efficient IFCXML computing modules and plug-ins for these commercial BIM platforms to promote the integration of BIM and blockchain. Researchers can also explore other approaches such as open BIM web service and the BIM Collaboration Format standard to minimize information redundancy for BIM and blockchain integration. Secondly, only one pilot study was carried out. Thus, the testing and the evaluation results can only be perceived as a proof of concept of the BIBP, rather than a final version for benchmarking performance or proof of compatibility to other production projects. Future works are recommended to fine-tune the platform and test and evaluate it in the logistics and on-site installation phases of the surveyed modular construction case and other construction projects. Thirdly, there is a lack of a systematic framework for forecasting the costs of a production-scale, commercial BIBP. Thus, a detailed cost assessment of the proposed BIBP is desired when better empirical data is available.

Although these limitations can be addressed through future research, the barriers to using BIBP in construction projects should not be underestimated. The Building Department in Hong Kong has a series of concerns regarding technological (e.g., decentralization level), organizational (e.g., top management support), and environmental (e.g., government support) aspects to help construction organizations, ranging from large to small, to adopt blockchain-based solutions. As the construction industry is historically known for its slow adoption of innovative solutions, the implementation of BIBP can be hindered by knowledge, attitudinal, industry, financial, technical, process, and policy-related barriers. Therefore, researchers should also study strategies to address each barrier and promote the adoption of BIBP.

8. Conclusions

This research developed a blockchain-enabled IoT-BIM platform (BIBP) for off-site production management in modular construction (OPM-MC) with a view to solving the issues of a single point failure (SPOF) in IoT networks and the provenance of BIM modifications. A design science research (DSR) method was adopted to develop a three-layer BIBP system architecture. Firstly, Infrastructure as a Service (IaaS) was designed with an IoT module and user interfaces to collect accurate data from daily production operations to blockchain BIM and allow user interactivity. Secondly, Blockchain BIM as a Service (BaaS) was developed by linking permissioned blockchain to BIM and extending the existing open BIM standard. Thirdly, Software as a Service (SaaS) was configured with decentralized applications to achieve knowledgeable processes with a consensus mechanism. The system architecture was implemented and then compared with the existing IoT-enabled BIM platform. It was found that BIBP can avoid a SPOF in IoT networks and ensure the provenance of BIM modifications with reduced storage costs in OPM-MC.

The limitations of this study provide chances for further investigation. First, the semantic differential transaction (SDT) approach is imperfect as it is still slow to process large BIMs. Researchers can explore other approaches such as open BIM web service, the BIM Collaboration Format standard, and the "signature" of IFC objects to minimize information redundancy for blockchain and BIM integration. Second, this research only applies the developed platform to one pilot project for testing its effectiveness. Future research can improve and extend the applicability of the platform to more practical projects to enhance its effectiveness. Third, a detailed cost assessment was not included for the initial platform establishment, deployment, storage, and ongoing maintenance. Thus, researchers should develop a framework for assessing the costs of a production-scale, commercial BIBP. Fourth, the complex nature of the barriers hindering the broader diffusion of BIBP in the construction industry. Therefore, future investigations can focus on integrated strategies to address the identified barriers.

Acknowledgement

The work presented in this paper was financially supported by the Hong Kong Innovation and Technology Commission (ITC) with the Innovation and Technology Fund (ITF) (No. ITP/029/20LP). This funding source had no role in the design and conduction of this study.

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