Blockchain-enabled IoT-BIM Platform for Supply Chain Management in Modular Construction

Xiao Li[1*], Weisheng Lu[2], Fan Xue[3], Liupengfei Wu[4], Rui Zhao[5], Jinfeng Lou[6], and Jinying Xu[7]

Abstract

Configuring a trustworthy IoT-enabled BIM Platform (IBP) is significant for modular construction to ensure transparency, traceability, and immutability throughout its fragmented supply chain management. However, most current IBPs are designed adopting a centralized system architecture, which fails to achieve a decentralized and effective one to ensure a single point of truth in BIM and prevent a single point of failure in IoT networks. To address this challenge, this study introduces permissioned blockchain with IBP and proposes a novel service-oriented system architecture of blockchain-enabled IoT-BIM platform (BIBP) for the data-information-knowledge (DIK) driven supply chain management in modular construction. Firstly, Infrastructure as a Service (IaaS) is designed with hardware, core technologies, and protocols to offer accurate data from daily practice to blockchain BIM. Blockchain BIM as a Service (BaaS) is then developed within the permissioned blockchain to ease the interoperability of the information, semantics, and meaningful inferences.

[1] Postdoctoral Fellow, Department of Real Estate and Construction, The University of Hong Kong, Hong Kong SAR.

Email: xl1991@hku.hk, Tel.: (852) 5537 0842, ORCiD: 0000-0001-9702-4153; * Corresponding author

[2] Professor, Department of Real Estate and Construction, The University of Hong Kong, Hong Kong SAR.

Email: wilsonlu@hku.hk, Tel.: (852) 3917 7981, ORCiD: 0000-0003-4674-0357;

[3] Assistant Professor, Department of Real Estate and Construction, The University of Hong Kong, Hong Kong SAR.

Email: xuef@hku.hk, Tel.: (852) 3917 4174, Fax: (852) 2559 9457, ORCiD: 0000-0003-2217-3693:

[4] Ph.D. student, Department of Real Estate and Construction, The University of Hong Kong, Hong Kong SAR.

Email: u3545425@connect.hku.hk, Tel.: (852) 6930 8019, ORCiD: 0000-0002-3768-9142

[5] Research Assistant, Department of Real Estate and Construction, The University of Hong Kong, Hong Kong SAR.

Email: ruizhao@hku.hk, Tel.: (852) 6998 6845, ORCiD: 0000-0003-1993-3129

[6] Ph.D. student, Department of Real Estate and Construction, The University of Hong Kong, Hong Kong SAR.

Email: waseljf@connect.hku.hk, Tel.: (852) 9423 1962, ORCiD: 0000-0001-5748-0146

[7] Postdoctoral Fellow, Department of Real Estate and Construction, The University of Hong Kong, Hong Kong SAR.

Email: jinyingxu@connect.hku.hk, Tel.: (852) 6025 1696, ORCiD: 0000-0001-9589-6396;

Furthermore, Software as a Service (SaaS) is configured with decentralized applications to achieve knowledgeable operations or processes with a crash fault-tolerant consensus mechanism. The demonstrative case study in a modular student residence project evaluates the proposed BIBP system prototype with the performance analysis of storage cost, throughput, latency, privacy, and feedback from stakeholders. The results indicate that BIBP has an effective system architecture with acceptable throughput and latency, can save storage costs to achieve a single point of truth in BIM, and avoid a single point of failure for IoT networks with privacy and security preserving mechanisms.

Keywords: Blockchain, IoT, BIM, Supply Chain Management, Modular Construction

1 Introduction

The construction industry contributed a considerable 13% share of global Gross Domestic Product (GDP) at 7% employment of the world's working population (Barbosa et al., 2017). However, it is encountering challenges such as declining total productivity, professional labor shortfall, and the aging workforce. To improve these issues, modular construction has been adopted worldwide, such as in Singapore (Hwang et al., 2018), UK (Innella et al., 2019), Canada (Liu et al., 2019), United States (Ramaji and Ali, 2016), Australia (Thai et al., 2020), and China (Liu et al., 2017). Practices in these countries have demonstrated its benefits, including shortened construction time, reduced site labor, minimized construction waste, and improved environment and safety (Li et al., 2019a).

Modular construction becomes more demanding in high-density and resource-limited cities, such as Hong Kong, which take advantage of supply chain management (SCM) to outsource every piece of prefabricated components and transport them to local sites for installation (Luo et al., 2020). However, the rising fragmentation of such supply chain has attracted much more attention from stakeholders for efficient collaboration, visibility, accountability, and traceability, especially as more expensive assets such as prefabricated modules and units are produced and shipped off-site with the travel restrictions during coronavirus pandemic (Li et al., 2021).

Academics and industry have collaboratively developed practical platforms for SCM in prefabricated construction by embracing Building Information Modeling (BIM) and Internet of Things (IoT) (Li et al., 2018a; Zhong et al., 2017; Xu et al., 2018; Zhai et al., 2019). These multi-dimensional IoT-BIM platforms can help collect near real-time data to increase visibility and traceability in production, logistics, and on-site installation. Different stakeholders can then track a project's cost and schedule (Li et al., 2020).

However, the current IoT-BIM Platform works in a centralized way, leading to several issues: (1) although IoT does establish the connections between construction resources (e.g., prefabricated modules) and BIM, it cannot ensure the single point of truth for any change in

BIM. It leaves room for human manipulation of BIM models without provenance (Xue and Lu, 2020); (2) random errors, noises, or malicious data generated from IoT sensors can result in a single point of failure for IoT networks, reducing data quality for BIM and negatively affecting the trustworthiness of IoT-BIM (Lee et al., 2021); (3) an open IoT-BIM platform can boost construction companies' competitiveness as more and more stakeholders (e.g., customers) under industry 4.0 prefer to be involved in the transparent construction processes (Lu et al., 2021). However, the privacy and security of the open IoT-BIM can not be guaranteed in the existing system architecture. These persistent issues challenge the extensive and profound impact of IoT-BIM solutions for SCM in modular construction.

Blockchain technology is well-known for its distributed database, trustworthy digital ledger, and a complete no-trust peer network with consensus protocols (Cachin, 2016). Recently, blockchain is also introduced into BIM and IoT to record the BIM modification history and build trust in the distributed IoT network (Zheng et al., 2019; Xue and Lu, 2020; Lu et al., 2021; Li et al., 2020). The integration of Blockchain and IoT-BIM may address the issues of the IoT-BIM platform in SCM of modular construction. However, configuring a blockchain-enabled IoT-BIM platform (BIBP) for SCM in modular construction is now staying at a concept rather than a developed system and is still in its infancy. Designing effective system architecture with lower storage cost, lower latency, and higher throughput to ensure a single point of truth for BIM and avoid a single point of failure of IoT is challenging.

Thus, this study aims to develop a brand new BIBP for SCM in modular construction. To this end, it has three concrete objectives: (1) establishing a Data-information-knowledge (DIK) driven supply chain management model for modular construction as a reference model for BIBP; (2) instantiating this theoretical model by proposing an effective system architecture of BIBP; and (3) validating the system architecture by implementing a prototype, using a case study as an evaluation experiment. The remainder of the paper is structured as follows. Subsequent to this introductory section is Section 2, which elaborates on related works of modular construction, supply chain management, IoT, BIM, and blockchain. Section 3 delineates a DIK-driven SCM model, followed by the BIBP system architecture. Section 4 provides a demonstrative evaluation experiment to illustrate and validate the functions and system architecture of BIBP. Finally, discussions are conducted in Section 5, and conclusions are drawn in Section 6.

2 Background

2.1 Supply Chain Management in Modular Construction (SCM-MC)

Modular construction is a revolutionary construction method whereby 3D-volumetric fully finished modules are prefabricated in off-site factories and then shipped to the construction site for installation (Yin et al., 2019). Modular construction is distinguished by an advanced planning and optimization approach for the supply chain. According to Mentzer et al. (2001), a supply chain is a network of actors (e.g., organizations or individuals) engaged in the flows of goods, services, finances, and information from a supplier to a customer. Therefore, SCM in modular construction can be defined as ensuring the flow of prefabricated products, services, data, information, and even knowledge to be smoothly delivered from production, logistics to on-site installation.

Handling SCM of modular construction well in practice is challenging due to the old-decade issues, such as lack of trust, fragmentation, and discontinuity. Trust is commonly understood as the positive expectations one party has about another party's intentions, and trust is fundamental for a transparent and secured supply chain (Luo et al., 2020). However, the construction industry is infamous for its lacking trust and prevalent adversarial relationship with one-off organizational settings, resulting in widespread claims, opportunism, risk aversion, less flexibility, mediocre quality, high cost, and poor value for money (MacLeamy, 2004; Bankvall et al., 2010). The most worth-noticing cases in SCM for lack of trust are product provenance issues and disputable inspection.

Fragmentation mainly results from the massive stakeholders and multiple stages (Hsu et al., 2019). SCM in modular construction involves more geographically distributed stakeholders, e.g., manufacturers, materials suppliers, and logistics agencies. To ensure resilient process management and assured quality, these stakeholders must keep frequent communication in multiple stages, e.g., design, production, storage, logistics, and on-site installation (See Fig.1). Thus, producing and delivering prefabricated modules at the right time and place to the right person requires a coordinated SCM system. However, the current SCM system in modular construction is inconsiderate and lacks multi-user-oriented functional modules, such as compliance check, process control, and quality assurance.

The discontinuity can be ascribed to the low level of information traceability and immutability. For example, product data collected from the factory to the construction site is still mainly dependent on manual operations and paperwork (Zhai et al., 2019). Therefore, such time-consumed manual processes may bring in input errors, file missing, and data tampering. Furthermore, logistic companies still fail to achieve just-in-time deliveries due to information delays, as the lack of a synergistic information platform hinders the visibility, traceability, and even knowledge-based business intelligence of SCM (Li et al., 2018a; Li et al., 2019b). Together, these pain points stimulate the need for data-information-knowledge (DIK) driven SCM models in modular construction to ensure improved data privacy, effective information sharing, rapid knowledge consensus.

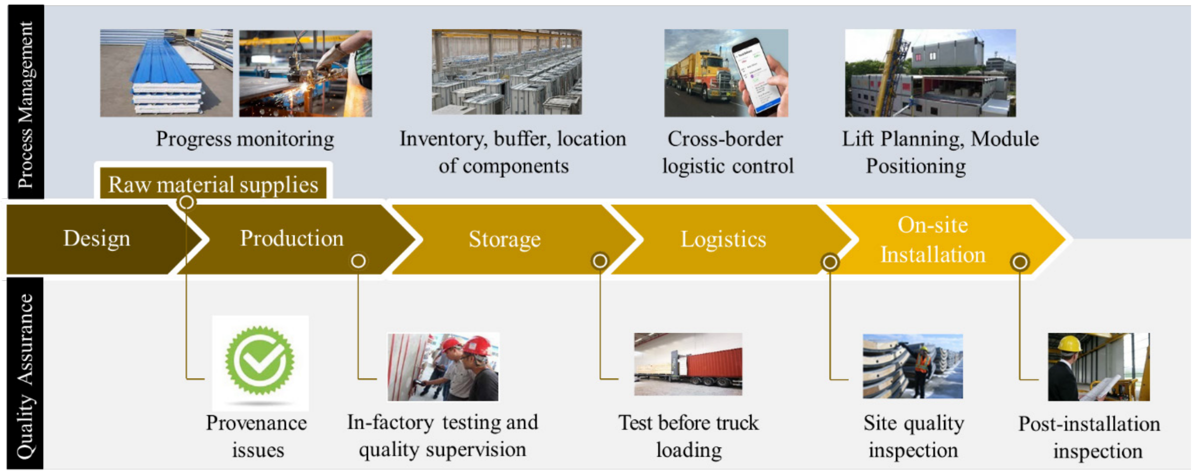

Figure 1. Process management and quality assurance in SCM-MC.

2.2 BIM, IoT, Blockchain, and their Integration

Building Information Modeling (BIM) has been widely used to improve the fragmentation and discontinuity in the construction SCM (Li et al. 2019a; Hijazi et al. 2021; Deng et al. 2019). The BIM kernel is "information," which helps stakeholders in construction SCM be informed of one another's operations through collaboration. The definition of the above information can be supported by OpenBIM. One of the most salient OpenBIM standards is the Industry Foundation Classes (IFC), a commonly used schema for data exchange that promotes BIM interoperability among stakeholders. However, effective communication and responsible decision-making among stakeholders require real-time interaction between the physical world and BIM.

The Internet of Things (IoT) is a growing concept that can help provide BIM with real-time data to link the physical resources with virtual BIM objects (Dave et al., 2018). Academia and industry have developed many enabling technologies to realize the concept of IoT, such as radio-frequency identification, near-field communication for short-range wireless (Xue et al., 2018), 5G for medium-range wireless (Li et al., 2018b), and low-power wide-area networking (e.g., LoraWan, NB-IoT) for long-range wireless (Mekki et al., 2018). Niu et al. (2016) also proposed a robust IoT model in construction, namely smart construction objects (SCOs), to augment construction resources with smartness.

Integrating IoT data with BIM in real-time has become an essential paradigm for developing digital twin applications to enhance construction productivity. These applications have been widely utilized in monitoring construction resource and progress (Li et al., 2018a), occupational health and safety management (Kanan et al., 2018), construction logistics and supply chain management (Zhong et al., 2017), and facility management (Cheng et al., 2020). To achieve these applications, it needs numerous building blocks, such as system architecture, open BIM standards for interoperability, and protocols of information integration and management (Xu et al., 2018).

Service-Oriented Architecture (SOA) is commonly used to develop IoT-enabled BIM platforms by combining various web services. However, SOA still lacks a useful design pattern to achieve real-time BIM model updates, two-way interactions between IoT and BIM, and integration with other technologies (e.g., blockchain). These mainly rely on the interoperable open BIM standards and protocols for IoT-BIM integration. Tang et al. (2019) also summarized five mainstream approaches for integrating time-series IoT data with contextual BIM data. For example, integrating semantics web (for BIM) and relational database (for IoT) has been identified as a promising hybrid approach for IoT-enabled BIM platforms. However, the integration of BIM and IoT alone is insufficient to ensure data privacy and security and truly achieve trust among stakeholders. For example, the shared cloud BIM model and its data can be manipulated, and IoT sensors (e.g., RFID, GPS) may suddenly be powerless or noises reported to reduce data quality. Blockchain seems to hold the key.

Blockchain is a distributed ledger of relevant data and transactions that are voluntarily agreed upon and shared across all peer-to-peer network users. (Nakamoto, 2008). Four components support a blockchain to function: cryptography, a distributed database, consensus mechanism, and smart contracts (Zheng et al., 2017). Cryptography, e.g., hashing algorithms, is applied to encrypt transactions based on the accepted protocol that makes the data hard to be tampered with (Beck et al., 2016). Distributed ledgers are also supported by an extensive network of computers, which records all data in each participant's ledger. The consensus defines the necessary agreement of maintaining network-wide synchronization of data transactions (Nguyen and Kim, 2018). Smart contracts are self-executing contracts that act automatically based on a consensus mechanism when certain trigger circumstances are met. (Buterin, 2014). Permissionless and permissioned blockchain platforms are now available. (Helliar et al., 2020). A permissionless blockchain is entirely decentralized, allowing anybody to access the data contained in blocks, such as Bitcoin and Ethereum (Buterin, 2014). Only a few recognized users can validate transactions and access block data in a permissioned blockchain., such as Hyperledger Fabric (Cachin, 2016). Permissionless blockchain emphasizes openness and decentralization, whereas permissioned blockchain uses deterministic consensus methods to increase throughput. (Gupta et al., 2020). This renders permissioned blockchains more accessible to projects at a time-sensitive level regarding transparency, traceability, immutability, decentralization, privacy, and smartness (Qian and Papadonikolaki, 2020). However, few studies have investigated blockchain technology in SCM of modular construction. For example, Wang et al. (2020) established a blockchain-based information management system for a precast supply chain to improve traceability and information communication. Zhang et al. (2020b) further investigated an integrated framework of the quality traceability system for prefabricated components.

In addition, numerous studies have explored the integration of blockchain and BIM, or integration of blockchain and IoT, separately. For example, Zheng et al. (2019) proposed a blockchain-based BIM data audit mechanism to record the BIM modification history and ensure the integrity and provenance of BIM data. Xue and Lu (2020) developed a semantic differential transaction approach to minimize information redundancy and improve information interoperability in integrating BIM and blockchain. Moreover, Lu et al. (2021) proved that blockchain could build trust in the distributed IoT network via a sidechain and provide confidence in such massive IoT-oriented data sources for construction SCM. Lee et al. (2021) designed an integrated digital twin and blockchain system for traceable data transmission. The blockchain authenticates and provides trust to all data transactions to the digital twin, while the digital twin updates BIM in near real-time utilizing IoT. The previous studies demonstrate that the fusion of blockchain and IoT-BIM may have the potential to address the current issues of IoT-enabled BIM platforms in SCM of modular construction. However, they mainly focus on data traceability. Developing and designing an effective system architecture with lower storage cost, lower latency, and higher throughput to ensure a single point of truth for BIM, avoid a single point of failure of IoT, and map the complex data-information-knowledge paradigm to the SCM processes/end-users is challenging.

2.3 Research Gaps

Through the above analysis, three observations can be summarized: (1) there is a lack of a useful operation model for guiding trustworthy, integrated, and continuous SCM in modular construction; (2) the development and configuration of functions, services, and applications with such model faces challenges, e.g., unaccountable data, inconsiderate information, and dull knowledge; (3) integration of blockchain with IoT-BIM could be the solution but need an effective system architecture at the current stage for further ensuring a single point of truth for BIM and avoiding a single point of failure of IoT.

3 System Architecture of BIBP

As SCM's business processes in modular construction are fragmented due to involving more stakeholders, stages, and technologies, data from multimedia and multi-modal information becomes more complex and semantically meaningful. Consequently, the cross-relation among various data in SCM processes brings the semantic information into the data, information, and knowledge (DIK) paradigm. The DIK paradigm has been a successful framework for combining and elevating the multimodal data into the models of information and knowledge (Zins, 2007; Zhang et al., 2020a). Thus, it can help map the evidence from SCM practice (data, e.g., facts, signals, symbols), system (information, e.g., semantics, descriptions, functions) to users (knowledge, e.g., cognition, decision, evaluation). This mapping has the potential to contribute to the design of BIBP via the following aspects: (1) It can connect the service, virtual and physical elements in SCM-MC business processes from the perspective of DIK; (2) It can help identify the data sources, information requirements, and knowledge applications in SCM-MC processes for BIBP; (3) It can help configure the BIBP network by forming design dimensions and system organizations.

3.1 DIK-oriented SCM-MC model

This study proposes a DIK-oriented SCM model for modular construction. As shown in Fig.2, this model presents its physical, virtual, and service layers with five dimensions: physical, data, information, knowledge, and service spaces.

The physical layer observes the real-time status of processes and resources in physical space (PS). For example, production-transportation-installation flow and construction objects (e.g., man, machine, material, method, environment (4M1E)) can serve in a decentralized IoT network. All data (e.g., structured, semi-structured, nonstructured) captured from PS can be mapped to data space (DS), and PS then communicates with the upper level through DS in a publish-subscribe manner.

The virtual layer tries to mirror the virtual resources and processes using BIM and make PS work at its optimal state by incorporating information space (IS) and knowledge space (KS). DS offers interfaces for IS and KS to access the data. IS can describe and function the geometric and non-geometric information from the virtual BIM environment. KS can integrate knowledge models (e.g., learning, prediction, evaluation, reasoning) to serve as a brain to handle various SCM issues (e.g., constraints, risks, uncertainties) in PS, DS, or IS.

The service layer bundles SCM processes and resources into services to make it easier for different SCM stakeholders in the service space (SS) to communicate.. For example, decentralized applications (Dapps) for process management and quality assurance could be stakeholders' immediate demands.

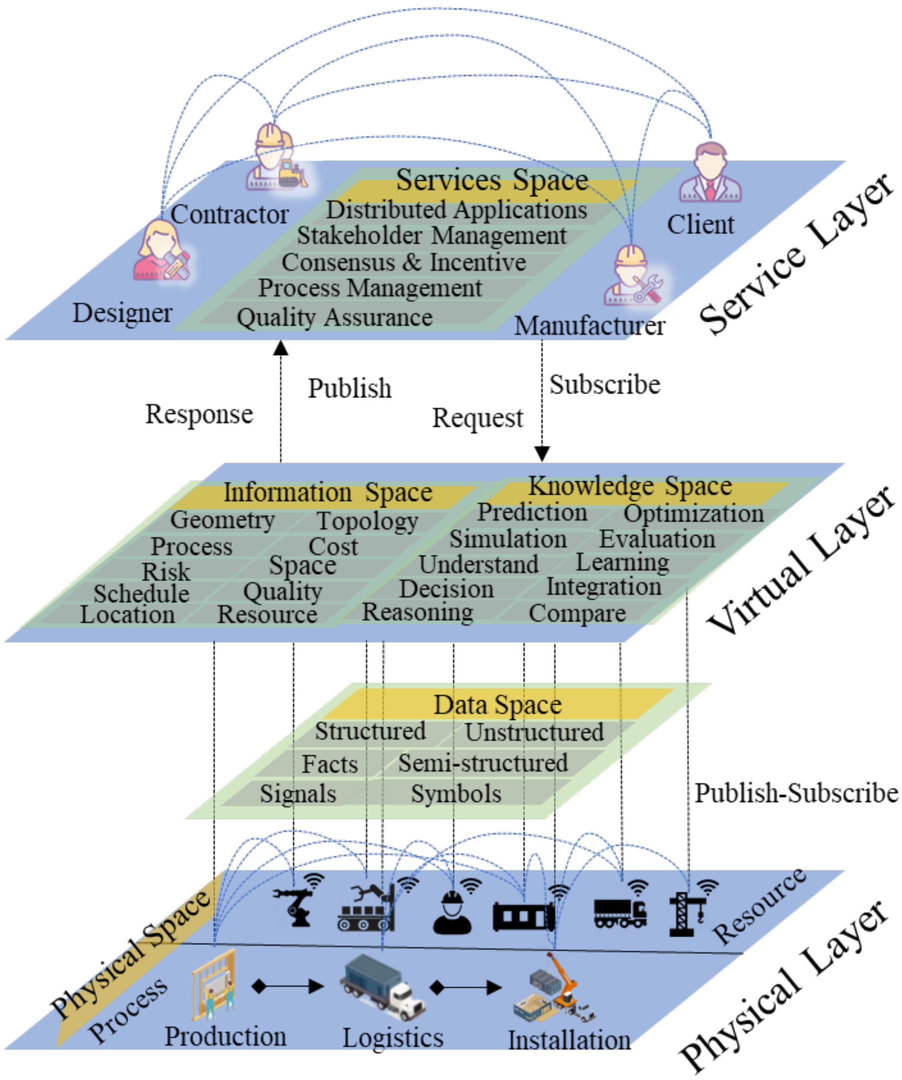

Figure 2. Three-layer DIK-oriented SCM model in modular construction

3.2 Overall System Architecture of BIBP

Based on the DIK-driven SCM model, BIBP is the integration of blockchain, IoT, and BIM, where IoT ubiquitously connects processes and resources in PS to the BIM-based IS while blockchain connects DS, IS and KS of BIBP with double chains in a secure, immutable, transparent, traceable, decentralized, and smart manner. Thus, BIBP is formalized as:

Definition 1 BIBP:= $\{PS_{IoT}, DS, IS_{BIM}, KS, SS\} \bowtie B_{PS-DS-IS-KS-SS}$

Where PS_{IoT} connects physical processes and resources of PS to virtual IS_{BIM}, DS, KS, and SS are the other three dimensions of BIBP. $B_{PS-IS-DS-KS-SS}$ denotes the blockchain networks and the transaction logics of five dimensions to support smart SCM in modular construction.

According to the BIBP definition, a system architecture of BIBP for configuring the DIK-driven SCM model is developed in Fig.3. Three layers and five dimension spaces in SCM are fused into a three-layer service-oriented architecture (SOA), including Infrastructure as a Service (IaaS), Blockchain BIM as a service (BaaS), and Software as a Service (SaaS). The platform uses the XaaS (Anything as a Service) paradigm to bridge the SCM practices and multiple stakeholders' demands in modular construction.

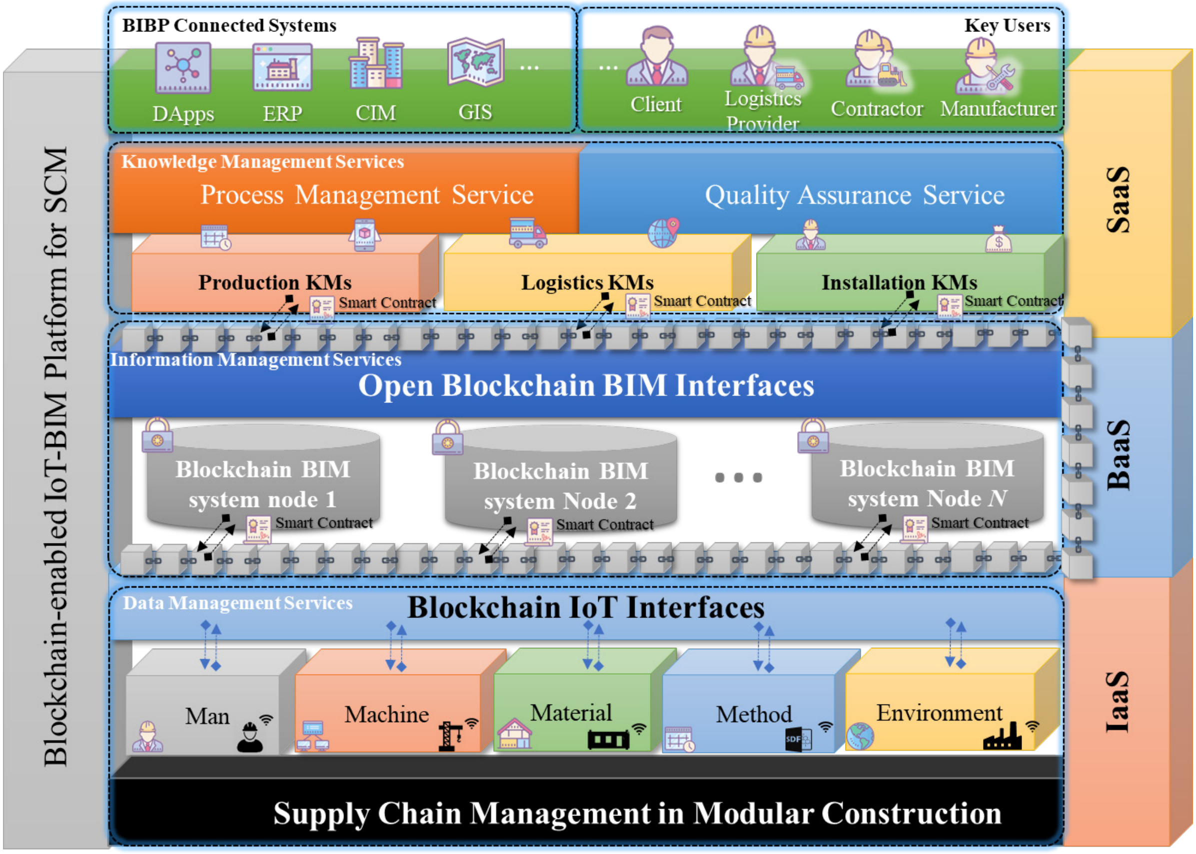

Figure 3. System architecture of BIBP for SCM in modular construction

IaaS includes hardware, core technologies, and protocols (e.g., IoT protocols and open BlockchainBIM standards), which are used to extract SCM data from daily practice to blockchain BIM. Each resource (4M1E) and process in SCM are connected with their virtual twin via IoT, serving as transaction monitoring nodes to observe statutes (e.g., disturbances, constraints, abnormal conditions). Blockchain IoT interfaces can offer local optimal-state operation control based on the smart contract. For example, the accelerometer mounted on prefabricated modules can help measure their vibrations during transportation. Once vibrations exceed the threshold, the accelerometer can publish this transaction proposal to the blockchain, and alerts to drivers and other stakeholders can be triggered by smart contracts when the proposed transaction has reached consensus in the decentralized network.

BaaS structure and interfaces hold the key to information management in the BIBP for interoperating the information, semantics, and meaningful inferences. There are two primary modules to achieve BaaS functionality. One is the blockchain BIM system to record the changes of BIM in the blockchain. The other is the open blockchain BIM interfaces, which extend IoT properties in IFC within the new blockchain BIM system. Based on the BaaS, knowledge models (KMs) for process management (PM) and quality assurance (QA) can be developed.

SaaS meets multiple stakeholders' demands with the applications of knowledge-based stakeholder communication, PM, QA, BIM, and IoT through various KMs. These applications collect statutes of resources and processes to perceive instantaneous SCM performance via learning and evaluation. And then, these applications invoke KMs via smart contracts to intelligently improve the performance of SCM in modular construction. Furthermore, all SCM resources and processes are grouped as DIK services within the blockchain to serve end users and other connected systems (e.g., ERP, city information modeling (CIM), GIS) in a service-oriented manner.

The system architecture of BIBP can not only connect physical construction resources to the virtual BIM system via traceable and authentic IoT but also define a smart contract-oriented PM/QA mechanism within the Blockchain BIM system to support the real-time improvement of SCM in modular construction. Furthermore, this configuration can allow BIBP to work as a whole to offer innovative SCM services, helping modular construction companies better compete in construction 4.0.

3.2.1 Infrastructure as a Service (IaaS)

The hardware and protocols in IaaS can serve in edge and cloud infrastructures (See Fig.4 (a)). The edge comprises IoT-enabled construction resources (e.g., 4M1E), communication protocols, gateway nodes (GNs), broker nodes (BNs), and computing unit nodes (CUNs). Construction resources include man (e.g., worker), machine (e.g., crane, vehicle), material (e.g., prefabricated modules), method (e.g., inspection standards), environment (e.g., production plant, construction site). The real-time statuses of construction resources are captured by IoT devices and sensors with various communication protocols. GNs work as the interface to preprocess the data from IoT and forward the unified data to BNs, CUNs, BIM nodes (BIMNs), and KM nodes (KMNs), meanwhile receiving and transmit their responses and orders to IoT-enabled construction resources. BNs assign proper CUNs to process the time-sensitive tasks at the edge or pass on the complex tasks to the cloud. BIMNs update the virtual models by incorporating the data from the edge. Cloud offers sufficient computing and storage capacity for BIM and KMs to handle computing-intensive but latency-tolerant tasks or share burdens from BNs and CUNs.

A smart IoT plan is proposed in IaaS, where smart IoT can also work as an information exchange agent is called an “oracle” in the blockchain. It can be a flexible board of IoT sensors. For example, inertial measurement units and air pressure units can compensate the

GPS positions on precise movements and height data. Furthermore, for facility management, a supplement of passive RFID and QR codes can adhere to the prefabricated modules for a long time. For certain IoT applications, a mix of diverse IoT design profiles can provide the best performance-price ratio. Fig.4 (b) shows some detailed IoT plans. The initial plan includes two models: (1) A single low-energy GPS sensor for LBS logistics offshore. (2) For off-site plant and on-site assembly PM/QA, high-frequency, numerous movements and environmental sensors are required.

Hardware and software protocols in the IaaS are designed to regulate the synchronization of SCM reality. As shown in Fig.4 (c), the SCM process involves several stages and various stakeholders. There are existing means to manage the SCM activities in practice, such as as-designed BIM, documents, and orders of prefabricated modules, construction IoT for SCM, and the progress monitoring system. Therefore, comprehensive hardware and software protocols fulfill the need to map and integrate the data in existing means and systems to the BIBP platform.

In comparison to existing blockchain systems in the construction industry, this research offers open blockchain IoT-BIM as the Infrastructure, which is based on an open BIM standard that is expanded from IFC. Extending the existing open BIM standard IFC (ISO 16739-1:2018) is a necessity in IaaS. Fig.4 (d) shows that the extended BIM standard can handle more functions than the conventional IFC standard. The new extension in IFC involves two parts. The first part is a semantic deferential transition (SDT) model developed by Xue and Lu (2020) for blockchain computability. As BIM models are usually massive in size, the blockchain cannot handle massive data due to network capability. Also, as shared by multiple stakeholders, BIM is subjected to simultaneous changes by different parties simultaneously. Therefore, a well-defined extension model to bridge the fundamental gap between the IFC and blockchain can manage the real-time, simultaneous changes as IFC change consensuses. The other extension to IFC is the IoT properties, which were non-existed in the current IFC properties. Examples include production line, logistics company, driver ID, defects, and maintenance history. These new IoT properties are attached to the IFC standard directly.

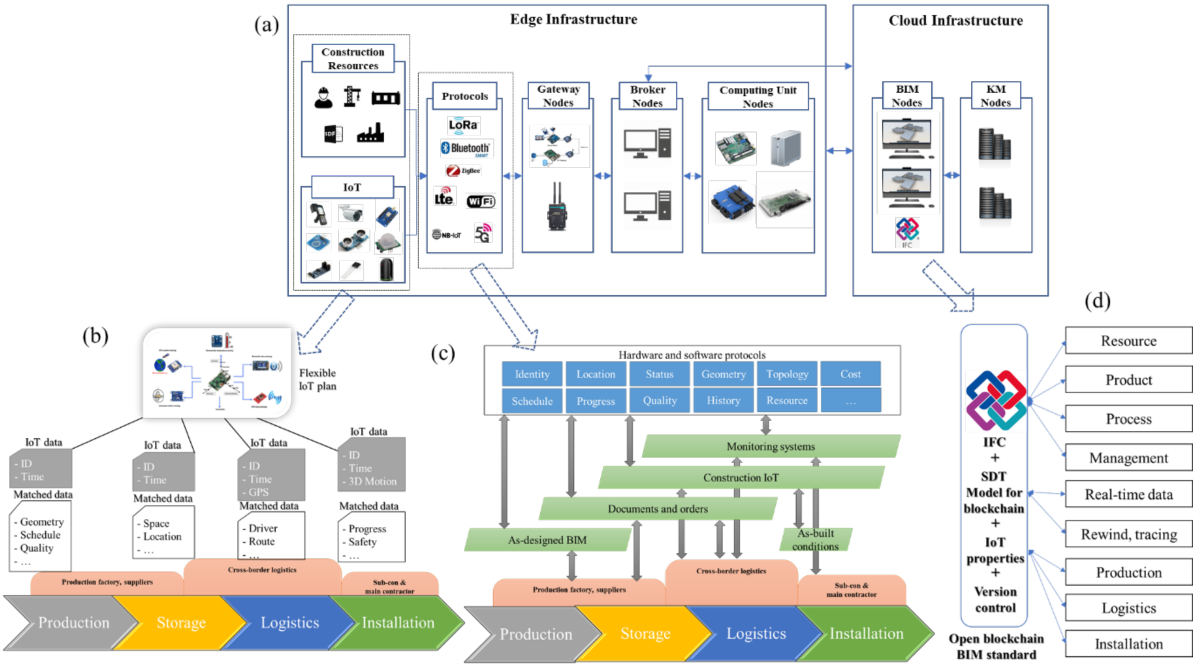

Figure 4. Hardware and protocols of BIBP.

3.2.2 Blockchain BIM as a Service (BaaS)

BIBP adopts the *Hyperledger Fabric* as the framework with the following advantages: a. it is a closed permission-based network that can provide higher throughputs and is very suitable for the scenario of project-based SCM in modular construction; b. it is under a modular architecture facilitating plug-in components development; c. It ensures consensus efficiency among peer nodes to enhance performance and scalability; d. Channels designed in Fabric offer a way to separate sensitive data; e. The Fabric with LevelDB facilitates query functions. BIBP includes the services of the BIBP network, ledger model, and smart contracts in BaaS.

(1) BIBP network service: As shown in Fig.5, the BIBP network is a double-chain (e.g., double channels in Hyperledger Fabric) structure that offers services of ledgers (*L1, L2*) and smart contracts (*S1, S2*) to facilitate DIK-driven agile SCM-MC. Each dimension of DIK-SCM-MC can be considered as an organization $R \subseteq \mathbb{R} = \{R_{PS}, R_{DS}, R_{IS}, R_{KS}, R_{SS}\}$ to join in a network, where any participant in an organization needs a verifiable identity that is issued with X.509 certificates by the corresponding certificate authority $CA \subseteq \mathbb{CA} = \{CA_{PS}, CA_{DS}, CA_{IS}, CA_{KS}, CA_{SS}\}$. For example, CA_{SS} distributes X.509 certificates to recognize the participants (e.g., client, manufacturer, logistics provider, contractor) affiliated to R_{SS}. Also, R_{IS} and R_{SS} control the network by defining the policy rules specified in network configuration (*NC*). They also serve as network administration points for ordering service O_{IS} and O_{SS}. R_{IS}, R_{KS}, and R_{SS} can form a consortium on channel #1 (*C1*) for knowledge-based SCM services, where *C1* is managed to comply with the policy rules defined in channel configuration (*CC1*) and can be described as:

$$\textbf{Definition 2}\ C1 := \{A_{SC}, \dots, A_{IPQ}, A_{BIM}\} \overset{S1}{\leftrightarrow} \{P_{SN}, P_{PQN}, P_{BIMN}\} \overset{L1}{\leftrightarrow} \{O_{IS}, O_{SS}\}$$

Where *C1* comprises a set of stakeholder peer nodes $P_{SN} \in R_{SS}$, a set of process management and quality assurance KMs peer nodes $P_{PQN} \in R_{KS}$, and a set of BIM peer nodes $P_{BIMN} \in R_{IS}$. DApps, such as stakeholder communication application A_{SC}, the intelligent PM-QA application A_{IPQ}, and BIM application A_{BIM} are allowed to connect with *C1* based on CA_{SS}, CA_{KS}, and CA_{IS}. Also, a smart contract packages *S1* is adopted to produce business service, knowledge, and information level transactions from DApps and peer nodes, and these transactions are then sorted into blocks by O_{IS} or O_{SS}, and broadcast the validated transactions to each peer node in the *C1* where they received the immutable copy of the ledger *L1*.

Furthermore, R_{PS}, R_{DS}, and R_{IS} can form another consortium on channel #2 (*C2*) to achieve efficient data and information management of DIK-SCM-MC. *C2* is governed by *CC2* and formalized as:

$$\textbf{Definition 3}\ C2 := \{A_{BIM}, \dots, A_{SCO}\} \overset{S2}{\leftrightarrow} \{P_{BN}, P_{CUN}, P_{BIMN}\} \overset{L2}{\leftrightarrow} \{O_{IS}, O_{SS}\}$$

Where *C2* includes a set of BNs P_{BN} and CUNs P_{CUN} , belonging to R_{DS}, and a set of BIM peer nodes $P_{BIMN} \in R_{IS}$. DApps, such as BIM application A_{BIM}, the IoT-enabled construction resources, named as smart construction objects (SCOs), for data and resources management application A_{SCO} are allowed to sit in the *C2* based on CA_{IS}, CA_{DS}, and CA_{PS}. *S2* is applied to generate operational data level transactions across DApps and peer nodes, which are then sorted into blocks by O_{IS} or O_{SS}, and broadcast the validated transactions to each peer node in the *C2* where they received the immutable copy of the ledger *L2*.

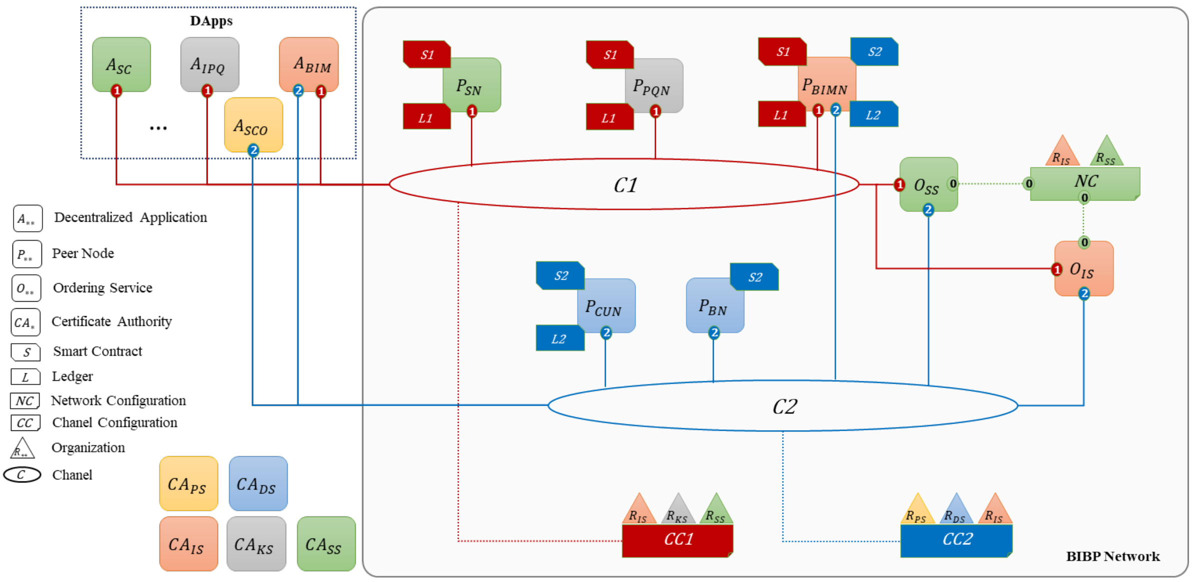

Figure 5. BIBP network

(2) Ledger service: the ledger stores factual information about SCM objects, namely, BIM-based PM and QA on *L1* for *C1*, and SCOs on *L2* for *C2*. A ledger is owned and retained by the decentralized peer nodes within the BIBP network. The ledger service in the BaaS contains two components: a world state and a blockchain (See Fig.6). The former presents the latest value of the objects' attributes, while the latter records the immutable history of all transactions that resulted in these current values of the world state. The world state is physically executed as a database (e.g., LevelDB, CouchDB) to offer simple and efficient storage and retrieval of ledger states. The blockchain is structured as a sequential log of interlinked blocks, where each block contains transactions in an ordered sequence, each transaction representing a query or update to the world state. Each block can be defined as a triple $B_i = \{H_i, D_i, M_i\}$. A block header H_i comprises three fields: block number, current block hash, and previous block header hash. Block data D_i includes an ordered sequence of transactions. These transactions are recorded when the ordering service O_{IS} or O_{SS} generates the block. Block metadata M_i includes a timestamp, the certificate, public key, and signature of the block creator. Each transaction T_i contains a header, a cryptographic signature and a proposal from DApp, responses as the smart contract's output, and endorsements from the required organizations with response signature.

As a blockchain data structure is standardized in a ledger model, the world states *W1* and *W2* in *L1* and *L2* can be defined as:

Definition 4 $W1 := \{\{\cup_i \langle K_i^{PM}, V_i^{PM}\rangle\}, \{\cup_l \langle K_l^{QA}, V_l^{QA}\rangle\}, \{\cup_m \langle K_m^{BIM}, V_m^{BIM}\rangle\}\}$

$$W2 := \left\{\{\cup_j \langle K_j^{SCO}, V_j^{SCO}\rangle\}, \{\cup_n \langle K_n^{BIM}, V_n^{BIM}\rangle\}\right\}$$

Where *W1* includes three key-value $\langle K, V\rangle$ pairs, namely, $\langle K_i^{PM}, V_i^{PM}\rangle$, $\langle K_l^{QA}, V_l^{QA}\rangle$ and $\langle K^{BIM}, V^{BIM}\rangle$, presenting the current knowledge states of the *i*th PM, *l*th QA and the *m*th changes of the BIM model, respectively. K_i^{PM} and K_l^{QA} denote the sequence number of SCM-MC processes and quality inspection procedures. V_i^{PM} and V_j^{QA} indicate a set of knowledge for K_i^{PM} and K_l^{QA}, including the results from optimization, simulation, prediction for PM and QA. K^{BIM} represents the identifier of the changes of the BIM model, and V^{BIM} indicates the properties of the changes of the BIM model, such as geometric and non-geometric information. Similarly, *W2* demonstrates the current data states of the *j*th SCO. K_j^{SCO} indicates the identity of IoT-enabled construction resources and V_j^{SCO} comprises the data regarding the resources, such as status, location, vibration, altitude, etc. In summary, each endorsed transaction causes the ledger to update the changing values of a key-value pair.

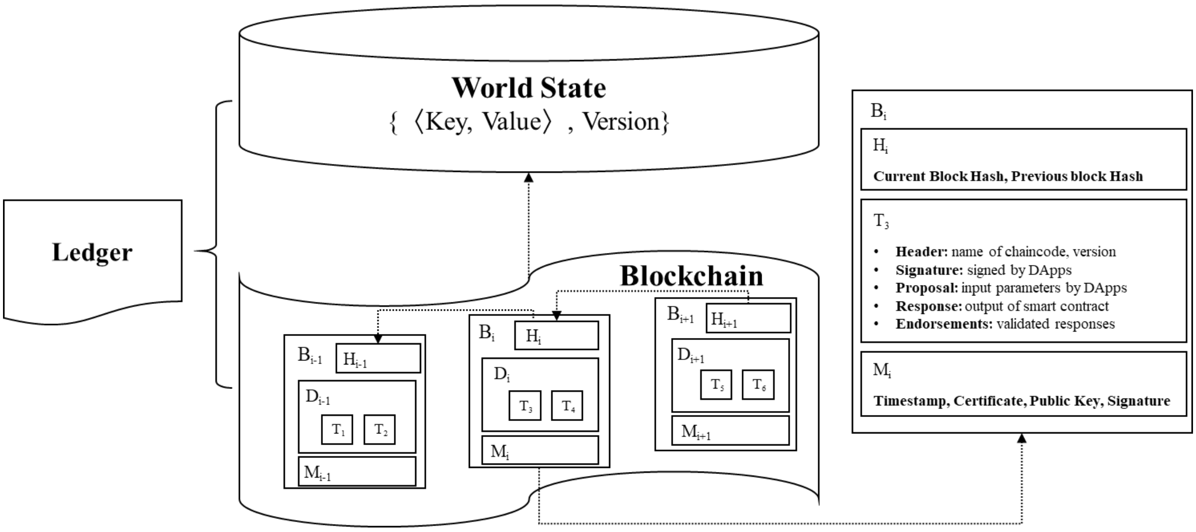

Figure 6. Ledger service model in BaaS.

(3) Smart Contract Services: Smart contracts define the executable logics between the five dimensions of SCM in modular construction that generate new facts added to the ledger, facilitating the optimal PM-QA of SCM. In BaaS, two chaincodes (smart contract packages), namely *S1* and *S2,* are deployed on *C1* and *C2*, respectively.

S1 comprises seven main smart contracts to support intelligent PM-QA of SCM, including value assessment contract (VAC), capacity assessment contract (CAC), availability assessment contract (AAC), process optimization contract (POC), quality control contract (QCC), BIM update contract (BUC), decision support contract (DSC). For a new order from a stakeholder, VAC, CAC, and AAC can help assess the order's business value, as well as the capacity and availability of resources and processes, and determine whether approve this order depending on the responses from the three smart contracts. Based on the approved order, A_{IPQ} makes an initial plan as the transaction proposal to *C1*, where POC and QCC first optimize and simulate the plan by invoking KMs and then offer the optimal plan. A_{BIM} can use BUC to record the BIM model changes caused by the order and plan. When reaching a consensus, the optimized PM-QA plan can be the input from BIM to *C2* by executing DSC.

S2 includes four primary smart contracts to manage the data-oriented services across *PS*, *DS*, and *IS*, namely, state validation contract (SVC), state computing contract (SCC), state evaluation contract (SEC), and state update contract (SUC). Each A_{SCO} perceives the statuses of construction resources and processes to understand current disturbance in PM and QA, and these states can be published as transaction proposals to *C2*. For a new proposal, SVC, SCC, and SEC can help check, compute, evaluate the data and then determine to approve the states if all three smart contracts produce positive responses. In the PM and QA, SUC can update the states to the A_{BIM}. A_{BIM} also subscribe to historical states and disturbances to learn the current PM and QA's performance and optimize future performance with appropriate KMs.

3.2.3 Software as a Service (SaaS)

All the DApps, such as stakeholder communication application A_{SC}, the intelligent process management and quality assurance application A_{IPQ}, BIM application A_{BIM}, SCOs management application A_{SCO} can work as SaaS in BIBP by involving consensus. The consensus is the convergence process of transactions through the BIBP network, where a consensus mechanism used in O_{IS} and O_{SS} can be applied to guarantee that the relevant peer nodes have agreed to a deal on the content and sequence of transactions. BIBP adopts *Hyperledger Fabric* as the core blockchain infrastructure in BaaS, and such permissioned blockchain works with a group of documented, defined, and frequently qualified peer nodes. Thus, BIBP uses a basic Crash Fault-Tolerant (CFT) consensus mechanism to control the transaction flow. As CFT in permissionless blockchain has no costly mining process such as PoW, it can reach higher throughput performance and lower latency. According to CFT, A_{SC}, A_{IPQ}, A_{BIM}, and A_{SCO} can be the representative services to achieve consensus transaction flow.

As presented in Fig.7 (a), a stakeholder communication begins with a transaction *T1* with the proposal *P*, which includes the details and specifications of the order proposed by a user (e.g., client stakeholder) via A_{SC}. A_{SC} chooses an identity from a wallet to decide this user's role and right to join *C1* via the gateway. A_{SC} then passes *P* proposed by the user via the private key to other peer nodes P_{SN}, P_{PQN}, and P_{BIMN}. P_{SN} assesses the business value of *P* by implementing VAC in *S1* and produces a response *R1* with the endorsement *E1* signed with the private key of P_{SN}. P_{PQN} and P_{BIMN} assess the status, capacity, and availability of process and resources with BIM by executing KMs based smart contracts, such as CAC and AAC, which produces *R2* with *E2* and *R3* with *E3*. A_{SC} then obtains endorsed responses and determines whether to proceed or end *T1*. When the endorsed responses reach a consensus, *T1* can be delivered to the ordering service. O_{IS} and O_{SS} pack these transactions into a new block and broadcasts it to all peer nodes on *C1*. Once the peer nodes validate this new block, it will be recorded on the *L1* of all peer nodes on *C1*. The peer nodes will then notify the connected DApp with the user that *T1* has been processed. A_{IPQ} takes the notified and entire order transaction from A_{SC} as the input to get the initial plans as transaction *T2* with proposal *P*, which is delivered to P_{SN}, P_{PQN}, and P_{BIMN}. P_{SN}, P_{PQN}, and P_{BIMN} optimize and simulate the plan with various constraints, risks, and uncertainties by executing POC and QCC, and generates *R1* with *E1*, *R2* with *E2*, and *R3* with *E3*. A_{BIM} then record any BIM model change caused by the order and plan as transaction *T3* with proposal *P*, and also need confirmation from P_{SN}, P_{PQN}, and P_{BIMN}. P_{PQN}, and P_{BIMN} can validate the change record and IFC objects by executing BUC and produces *R2* with *E2* and *R3* with *E3*. P_{SN} can reach a consensus to confirm the results presented in BIM using DSC and generate *R1* with *E1*.

Fig.7 (b) demonstrates a transaction flow for data and information-oriented PM-QA of SCM. Once *T2* is generated in *C1*, A_{BIMN} may conduct cross-chain delivery to transform the optimal plan into practical operations in *C2* as transaction *T1* with proposal *P* to guide the operations of PM and QA in *PS*. P_{CUN} and P_{BIMN} can visually present and analyze the operation considering the current status of resources and processes by executing SCC and SEC. During the PM-QA processes, each A_{SCO} publishes a real-time status as the transaction *T2* with proposal *P*, which is delivered to P_{BN}. P_{BN} help judge whether there is an abnormal and complexity by implementing SVC and provides *R1* with *E2*. If *R1* presents an abnormal and complexity, P_{BN} deliver this state to P_{BIMN} for further KMs processing by using SUC and generates *R2* with *E2*. If *R1* indicates a normal and simple condition, P_{BN} deliver this state to P_{CUN} for processing by using SCC and generates *R3* with *E3*. P_{BIMN} subscribes all the statuses from P_{SCON} to assess the current states and improve the future performance by executing SEC with learning and prediction capacity. Besides, O_{IS} and O_{SS} capture these transactions and order them into a new block to update *L2*.

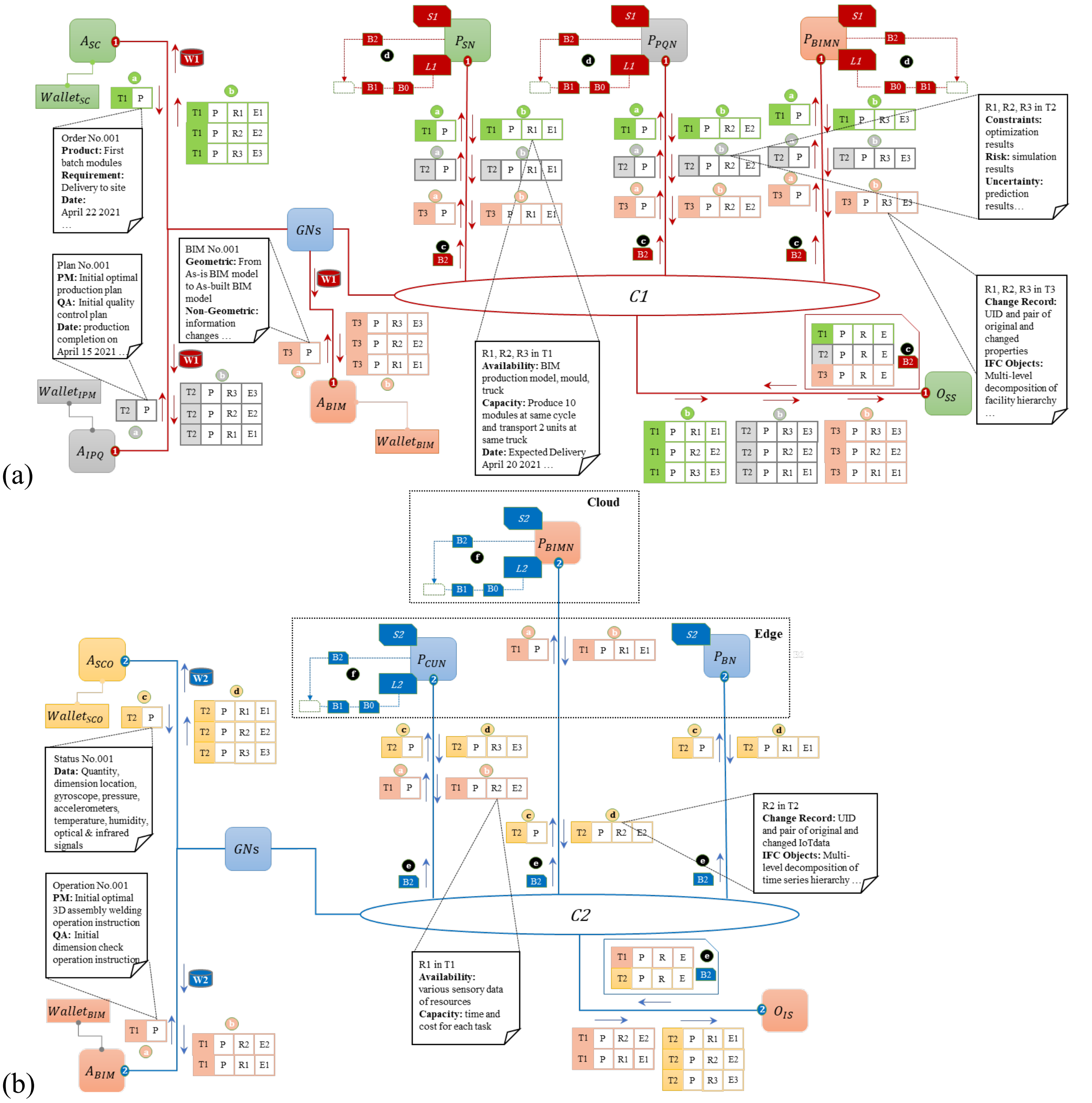

Figure 7 Service-oriented transaction flow on (a) C1; and (b) C2.

4 Implementation and Evaluation

4.1 Case Study

A modular construction project in Hong Kong is used to test the BIBP in its SCM. This project is a student residence with two 17-floor towers comprising 1224 prefabricated hostel rooms and other supporting facilities (e.g., prefabricated toilet, kitchen). The graphical details of the project are shown in Fig. 8. Fig.9 demonstrates the processes of SCM in this project, including the production, logistics, and installation. Apart from the consultancies of architect, structure, and building service, the primary stakeholders in this project include HKU Estate Office (owner), Paul Y. Engineering (general contractor), Yahgee Modular House (manufacturer). All these stakeholders can access the BIBP through the peer nodes of P_{SN}. In this case test, each peer node for each stakeholder is a docker deployed in the server. The typical scenarios, e.g., intelligent process management and quality assurance, BIM status updates, IoT sensing and tracking, are included. The following steps illustrate the transaction logic in each application scenario: (1) The peer nodes handle transaction proposals from DApps by implementing smart contracts and produce responses with endorsements. (2) DApps receive certain transactions with responses and endorsements from peer nodes and sign their validity. (3) Ordering service nodes package the valid transactions into new blocks and distribute them to the related network's peer nodes. (4) The transactions in new blocks are then validated by each peer node and are thereby added to the ledger and dedicated to the network to notify DApps.

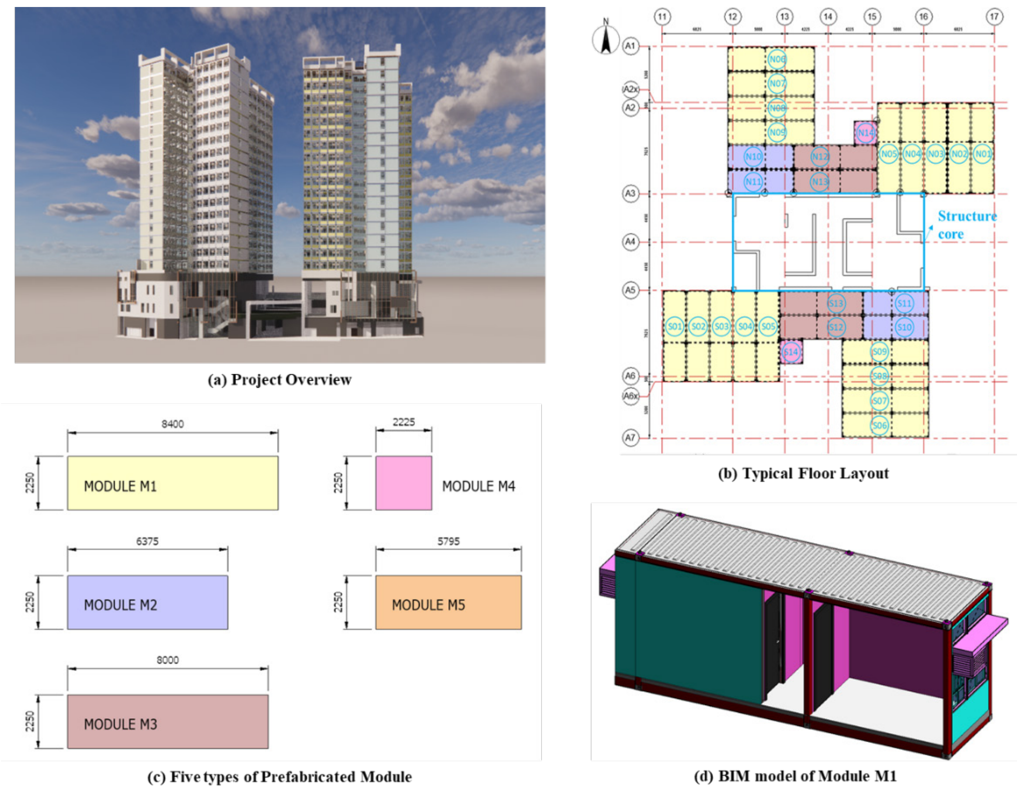

Figure 8. Overview of the MC project for this experiment: (a) project overview; (b) typical floor layout; (c) five types of prefabricated module; and (d) BIM model of Module M1.

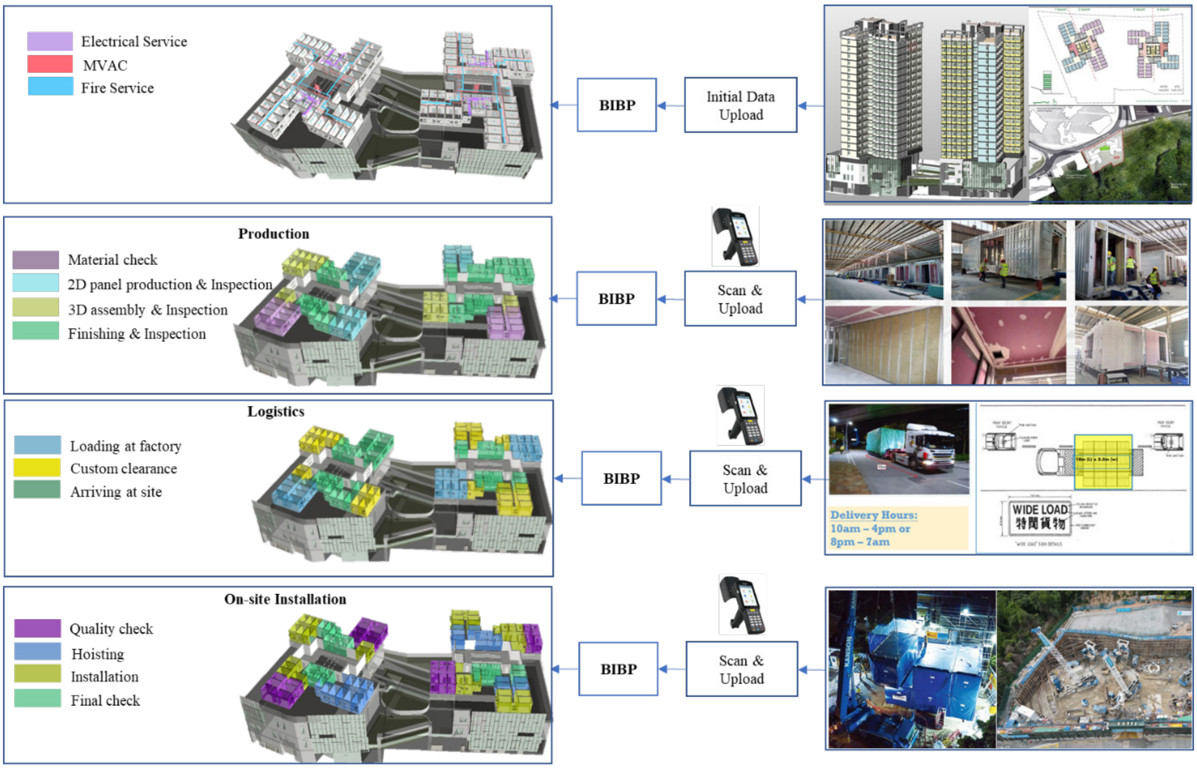

Figure 9. SCM process in BIBP for modular construction

In this case study, the passive RFID is used as the IoT plan to track the process status of SCM in modular construction. The RFID tags are stuck to the modular units, and near-field communication tags are embedded in the truck. The BIBP GN is a data converter in the production factory, transportation vehicles, and construction site. All RFID events are captured through A_{SCO}, computed via CUNs, validated and stored in the *C2* of BIBP, which can be broadcast among all the participants. The validated processes are demonstrated in different colors through A_{BIM}, such as grayish-yellow (3D assembly & inspection), dark green (arriving at the site), dark blue (hoisting). These status changes (e.g., format: {'ifcprocess':{'Material Check'→'2D Panel Production'}}) in the BIM model can be finally updated into the *C1* of BIBP. KM for QA/QC in A_{IPQ} is used to inspect the components or modules completed by the previous task, such as measuring the geometric differences between the as-built and as-designed models. The truck is recognized and confirmed by identifying the truck's NFC tags.

4.2 Prototype System

The BIBP was built using *Hyperledger Fabric* (version 1.4), and the smart contracts in the chaincodes were written using Javascript. The development environment was Ubuntu 18.04, and docker with isolated containers consumes fewer hardware resources to ease system prototype development than virtual machines. Using SpringBoot (version 2.4.0) and AdminLTE (version. 3), we created backend and front-end prototypes for each peer node, including frameworks, tools, and components (see Fig. 10). SpringBoot is a Java backend framework for web server and MySQL development. AdminLTE is a front-end framework based on Bootstrap that provides rapid development with responsive, reusable, and widely used components.

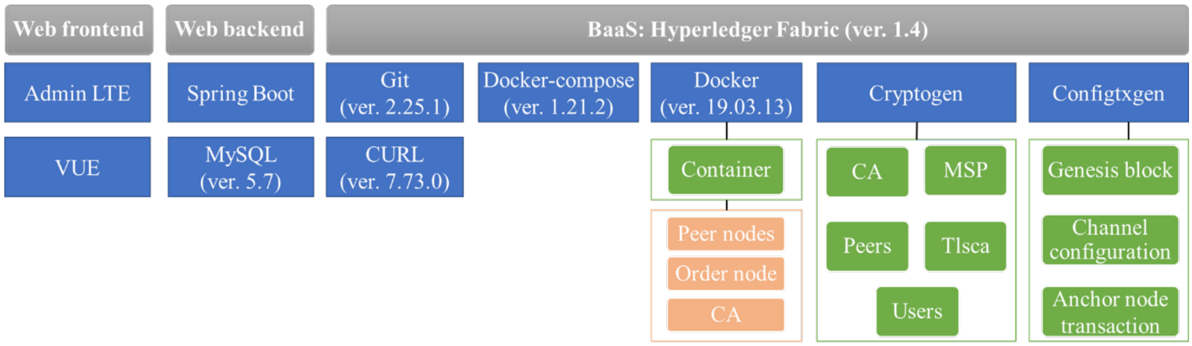

Figure 10. Frameworks, tools, and components involved in this prototype development.

In the prototype, P_{SN}, P_{PQN}, and P_{BIMN} are connected to form the *C1* in *Hyperledger Fabric* for upper smart PM-QA in SCM. *C2* includes P_{BIMN} and other functional nodes (P_{BN} and P_{CUN}) to facilitate accurate status tracking and operations of PM-QA in SCM. Other external systems and DApps are also connected with the *Hyperledger Fabric* to facilitate the above executions. Networks, channels, chaincodes, blocks, transactions, membership service provider (MSP), and ordering service are all part of the BIBP.

Fig. 11 (a) presents the BIBP network details, which includes five-dimension organizations (PS, DS, IS, KS, SS), two orders, and one cross-chain peer node (P_{BIMN}). Fig.11 (b) (c) demonstrates the examples of the web front end of the *C1* and *C2*, in which the *Hyperledger Fabric Cello* graphical interfaces provide the comprehensive network composition, organization information, peer nodes, and chaincodes (see Fig.11 (d)). Each block stored transactions (20 transactions at most) that keep PM-QA events and links with other blocks based on their hash values to compose *L1* and *L2*. The block size is configured to 98 MB, and CouchDB is applied for word state cache and retrieval. *C1* includes six peer nodes and one chaincode (*S1*), while *C2* contains three peer nodes and one chaincode (*S2*) heretofore. Six peer nodes in *C1* correspond to the peer nodes in P_{SN}, P_{PQN}, and P_{BIMN}. There are four peer nodes are involved in P_{SN}: (1) the owner, who is also the orderer in the O_{SS}; (2) the contractor; (3) the manufacturer; (4) the logistics agency. Each of P_{PQN} and P_{BIMN} has one peer node in *C1,* and each of P_{BIMN}, P_{BN}, and P_{CUN} has one peer node in *C2*.

Fig.12 presents the configuration information for these nodes, and cryptogen in *Hyperledger Fabric* is used to ease the registration process by generating certificates such as admincert (for each node's administrator), cacert (for the order), and tlscacert (for the transaction) (for establishing connections). Each peer node has an administrator registered in either *C1* or *C2*. At the back end, MSP handles CAs with various dimensions of SCM and the wallets of DApps, which ensures peer nodes can receive certificates and public-private keys as the cryptographic identities. The administrator can also send requests to the sidechain's Fabric CA for offering certificates and the public-private key to operators in the associated organization, who are in charge of adding operation records to the sidechain. The ordering service, consortium, and each peer node are all configured in the *C1*'s genesis block. In each peer node, an anchor peer P_{BIMN} is created for cross-node communication in the *C1* as well as cross-chain interactions between the *C1* and *C2*. By collecting transactions, bundling them into a block, and distributing the block to peer nodes, the ordering service (configured in Fig.10) makes it easier to achieve an agreement on the sequence of transactions.

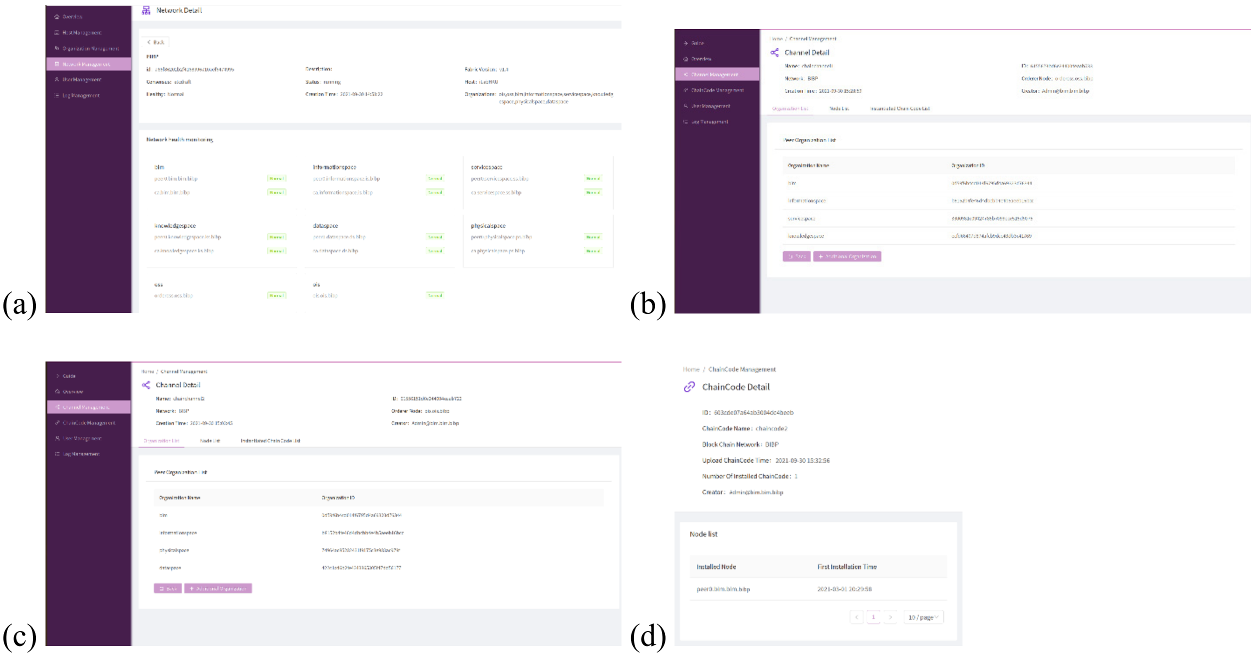

Figure 11. BIBP prototype system: (a) BIBP network details; (b) C1 details; (c) C2 details; and (d) chaincode details.

```yaml
Orderer:
  Addresses: &ref_6
    - 'ordeross-oss:30000'
    - 'ois-ois:30001'
  BatchSize: &ref_7
    AbsoluteMaxBytes: 98 MB
    MaxMessageCount: 100
    PreferredMaxBytes: 8192 KB
  BatchTimeout: 2s
  EtcdRaft:
    Consenters: &ref_8
      - ClientTLSCert: >-
          crypto-config/ordererOrganizations/oss.bibp/orderers/ordeross.oss.bibp/tls/server.crt
        Host: ordeross-oss
        Port: '30000'
        ServerTLSCert: >-
          crypto-config/ordererOrganizations/oss.bibp/orderers/ordeross.oss.bibp/tls/server.crt
      - ClientTLSCert: >-
          crypto-config/ordererOrganizations/ois.bibp/orderers/ois.ois.bibp/tls/server.crt
        Host: ois-ois
        Port: '30001'
        ServerTLSCert: >-
          crypto-config/ordererOrganizations/ois.bibp/orderers/ois.ois.bibp/tls/server.crt
    Options: &ref_9
      ElectionTick: 10
      HeartbeatTick: 1
      MaxInflightBlocks: 5
      SnapshotIntervalSize: 20 MB
      TickInterval: 600ms
  OrdererType: etcdraft
  Organizations: null
```


Figure 12. Order configuration

4.3 Performance Analysis

This section introduces the storage cost, throughput, and latency performance measures used to assess the BIBP prototype in the experiment. There are two assumptions: (1) A total of 40 modular products (one typical floor) are produced, transported, and installed in 60 days; (2) each modular product generates an average of 34 transactions (one order from A_{SC}, eleven PM-QA operations in A_{IPQ}, eleven status updates in A_{BIM}, eleven times data collection by A_{SCO},). T_{block} = 2 hours/block (12 working hours per day) can be used as the block time, which means a new block is created every half minute for recording SCM-MC transactions. As a result, based on a preliminary calculation, each block contains an average of four transactions.

4.3.1 Storage Cost

In the previous IoT-enabled BIM platform, the BIM model is stored in the webserver with the size can be around 128.84 MB (e.g., BIM model in Fig.9). To make the BIM model the single point of truth, we need to save the BIM model into the blockchain. However, it may lead to redundancy in the blockchain network if the BIM model's full information is stored in the blockchain network. In BIBP, any status change of the BIM is computed as the minimum SDTs. One transaction's average size can be reduced to 1 KB (Xue and Lu, 2020), and all of the detailed information is kept in a local database. The total number of transactions in this experiment is 1360 (40 × 34) and the maximum scenario in each ledger of the network for the experiment only generates1360 KB (1360 × 1). For the present blockchain storage capacity, it is a suitable size. Storage burdens may be freed from the BIBP system architecture, especially useful for tracking vital information in big BIM files.

4.3.2 Throughput and Latency

Fig. 13 presents the throughput simulated and measured at peer nodes by transactions per second, while the latency performance was tested by measuring the time of peer-to-peer transactions. Both metrics are simulated by changing the block size. When the block size is 98 MB, the findings show that the *Hyperledger Fabric* can reach an acceptable throughput of around 331 transactions per second (TPSs) with a latency of about 100 ms. The system's latency is measured in milliseconds, as evidenced by the result. Each transaction may be published minutes or hours apart in actual SCM procedures for modular construction. Some material supply and production activities are also long processes that might take up to a day. As a result, the prototype's latency may be acceptable. This analysis established that permissioned blockchains, such as *Hyperledger Fabric*, are suitable for BIBP.Moreover, the performance of *Hyperledger Fabric* in throughput and latency has also been validated in other studies to indicate it outperforms Ethereum (Pongnumkul et al. 2017; Dabbagh et al. 2020).

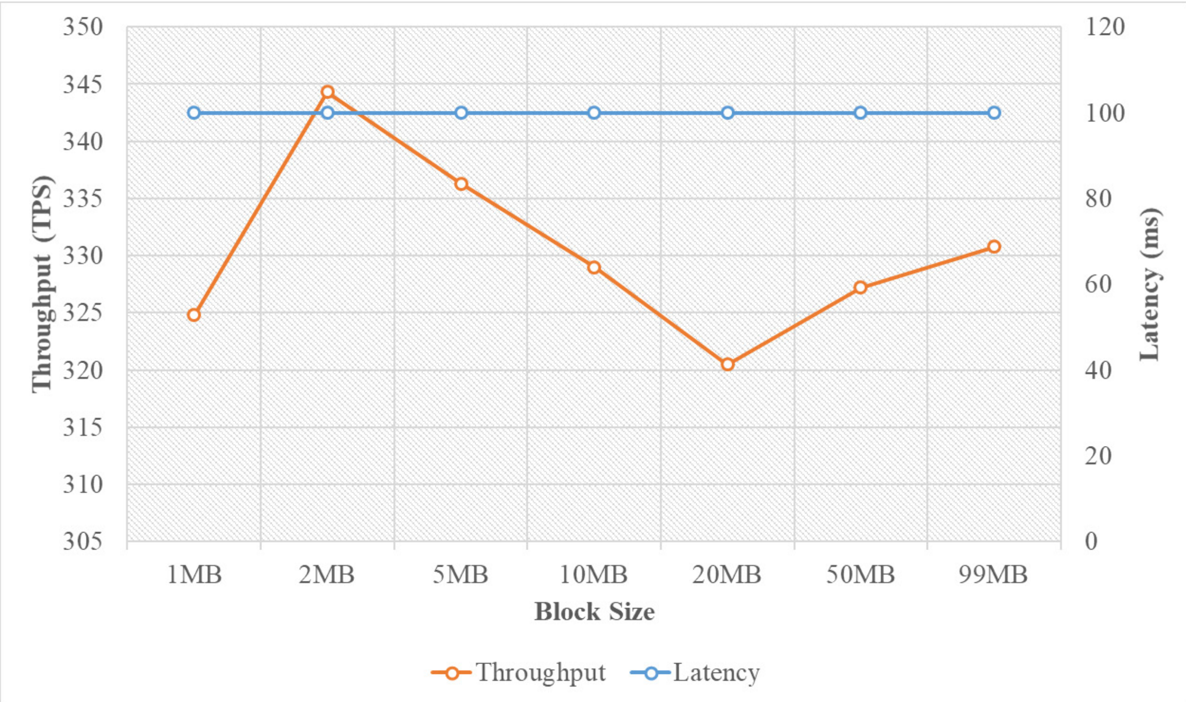

Figure 13. Throughput and latency of the prototype system

4.3.3 Privacy and Security Analysis

According to Lu et al. (2021) and Li et al. (2021), the privacy and security analysis of the proposed BIBP (particularly for the IoT network) can be explored via confidentiality, integrity, non-repudiation, authentication, and authorization.

Confidentiality: thanks to its cross-chain design (e.g., two channels in *Hyperledger Fabric*) and private data, this study can maintain confidentiality and private data. The former facilitates IoT-related operations by creating channel #2, allowing transactions to be accessed exclusively by peers (e.g., $P_{BN}, P_{CUN}, P_{BIMN}$) who engage in channel #2. The latter implies that transactions are encrypted with a hash and kept in the private database of authorized peers. As a result, the suggested method protects both privacy and confidentiality.

Integrity and non-repudiation: A transaction's integrity cannot be compromised while it is being sent. All transactions in channels #1 and #2 are tamper-proof and include timestamps. Furthermore, Transport Layer Security in *Hyperledger Fabric* allows transaction integrity check across peer nodes to avoid "man in the middle" attacks and otherwise secure connections.

Authentication: Authentication mechanisms rely on digital signatures, which necessitate the possession of two cryptographically corresponding keys by each peer node: a public key that is widely distributed and serves as an authentication anchor and a private key used to generate digital signatures on transactions.

Authorization: MSP in *Hyperledger Fabric* is used in this study to prove the identity of authorized peers. Smart contracts can only be activated by approved peers.

4.3.4 Feedback from Stakeholders

The primary stakeholders provide positive feedback on this prototype development. For example, HKU Estate Office (owner) said, " We now understand how the physical BIBP is set up amongst the project stakeholders and know the virtual process of transaction flows in the BIBP prototype". Paul Y. Engineering (general contractor) praised, "It is a uniform and open BIBP system suitable for different functions (e.g., inspections, progress monitoring, authentic data selection, privacy preservation) with involving different stakeholders." And "We truly understand the immutability in BIBP through the chained blocks with hashed transactions and stakeholders' consensus." Yahgee Modular House (manufacturer) commented, "It is not easy to graphically visualize and monitor the data-information-knowledge transactions operation process, but we understand the rationality of how the IoT data (via a hash table, dictionary-like data structure), inspection form (via URL), and BIM information (via changes in IFC) stored and validated on the BIBP." And "we learned that decentralized applications, such as quality inspection apps, how to interact with BIM, IoT, and blockchain system."

5 Discussion

Three features of originality to the proposed BIBP system design are outlined below in comparison to previous studies.

- First, by combining blockchain, IoT, and BIM, BIBP can inherit the merits of permissioned blockchain for SCM of modular construction in secure communication, accountable operations, traceable data, transparent information, and reliable knowledge when compared with existing IoT-enabled BIM platforms. BIBP can not only minimize manual interruption to SCM processes via establishing ubiquitous IoT among physical construction resources but also integrate BIM-based functional nodes and knowledge model nodes to construct an SCM network in modular construction.
- Secondly, in comparison to current blockchain systems in the construction industry, this research offers open blockchain IoT-BIM as the Infrastructure, which is based on an open BIM standard that is expanded from IFC. Therefore, the BIM in consensus and BIM in the local cache are IFC compatible. The open BIM standard can help the public body (e.g., government agency reluctant to mandating commercial software) access and assess the BIMs developed on commercial platforms. New information and functions are also easy to implement on an open BIBP.
- Thirdly, DApps for stakeholder communication, intelligent PM-QA, BIM, and IoT are designed with various smart contracts in SaaS. Moreover, the consensus-oriented transaction flow has been proposed in BIBP to achieve on-chain, cross-chain, and off-chain activities. The case study-based experiment has also indicated lower storage cost and acceptable latency and throughput than the traditional IoT-enabled BIM platform.

Despite these advancements, this study faces a few limits and problems in terms of practical use.

- Firstly, although the SDT can reduce the BIM model's redundancy, transactions in the PM-QA process of SCM are more complicated since the data, information, and knowledge, e.g., the analysis and solutions for constraints, risks, uncertainties, and disturbances, are dynamic and massive. Including them in each transaction can also lead to redundancy and low latency for the blockchain network. These complex transactions also prevent knowledge-based real-time optimization and control tasks. Thus, the extension of SDT to the knowledge models is needed.
- Secondly, constraints, risks, uncertainties, and disturbances in the PM-QA processes of SCM in modular construction are complex and dynamic, and current smart contracts are almost deterministic. How to develop adaptive smart contracts to process these data, information, and knowledge is still challenging. As the complex SCM process of modular construction may require various knowledge models, they are not be elaborated and tested in this study.
- Thirdly, the BIBP currently stays at the one case study experiment. It should be further developed and tested in more real off-site construction projects (e.g., modular, prefabricated, or panelized construction) based on the well-explained business process

analysis, completed open BIM standard, comprehensive IoT protocols, robust blockchain network with adaptive smart contracts, optimal block size, efficient consensus mechanism, and other Dapps or externally connected systems (e.g., ERP, GIS, CIM).

6 Conclusion

This study presents a service-oriented and decentralized system architecture of BIBP by linking three-layer and five-dimension SCM to support knowledge and information-driven smart SCM services and data-driven SCM operations in modular construction. BIBP integrates blockchain with IoT-BIM for configuring DIK-driven SCM in modular construction toward construction 4.0. BIBP was explained based on its DIK-oriented SCM model, system architecture, IaaS (e.g., hardware, core technologies, and protocols), BaaS (e.g., BIBP network service, smart contract service, ledger service), and SaaS (e.g., DApps and transaction flow). Significant contributions are summarized threefold based on the findings in this study. Firstly, a brand new BIBP system architecture for configuring SCM in modular construction was developed by connecting blockchain with the IoT-BIM. BIBP embraced significant merits in communicating information with security and transparency, and conducting operations with traceability and smartness while reducing competitive storage cost and achieving acceptable throughput and latency performance. Secondly, the configuration of IaaS, BaaS, and SaaS offered insights into the future industrial implementation of BIBP. Thirdly, the prototype system and its case study evaluation improve the feasibility of BIBP for SCM in modular construction. The experiment results indicated that the BIBP could carry out lower storage costs and reasonable throughput and latency. Future studies can improve and upgrade the proposed BIBP. For example, the design of the optimal consensus mechanism to achieve lower latency performance when increasing the number of transactions and the size of blocks, and also the development of adaptive smart contracts to more efficiently process complex data, information, and knowledge, such as constraints, risks, uncertainties, and disturbances in SCM of modular construction, by customizing the latest machine learning approaches.

Acknowledgments

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.

Data Availability Statement

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

List of Abbreviations

AAC	Availability Assessment Contract
BaaS	BIM as a Service
BIBP	Blockchain-enabled IoT-BIM Platform
BIM	Building Information Modeling
BNs	Broker Nodes
BUC	BIM Update Contract
CAC	Capacity Assessment Contract
CC	Channel Configuration
CFT	Crash Fault-Tolerant
CUNs	Computing Unit Nodes
Dapps	Decentralized Applications
DIK	Data-Information-Knowledge
DS	Data Space
DSC	Decision Support Contract
GNs	Gateway Nodes
IaaS	Infrastructure as a Service
IoT	Internet of Things
IS	Information Space
KM	Knowledge Model
KS	Knowledge Space
MC	Modular Construction
MSP	Membership Service Provider
NC	Network Configuration
POC	Process Optimization Contract
PM	Process Management
PS	Physical Space
QA	Quality Assurance
QCC	Quality Control Contract
SaaS	Software As A Service
SCC	State Computing Contract
SCM	Supply Chain Management
SCOs	Smart Construction Objects
SDTs	Semantic Differential Transactions
SEC	State Evaluation Contract
SOA	Service-Oriented Architecture
SUC	State Update Contract
SVC	State Validation Contract
SS	Service Space
VAC	Value Assessment Contract
4M1E	Man, Machine, Material, Method, Environment

References

Bankvall, L., Bygballe, L., Dubois, A., & Jahre, M. (2010). Interdependence in supply chains and projects in construction. *Supply Chain Management*, *15*(5), 385-393.

Barbosa, F., Woetzel, J., & Mischke, J. (2017). Reinventing Construction: A Route of Higher *Productivity*. McKinsey Global Institute.

Beck, R., Stenum Czepluch, J., Lollike, N., & Malone, S. (2016). Blockchain–the gateway to trust-free cryptographic transactions.

Buterin, V. (2014). A next-generation smart contract and decentralized application platform. *white paper*, *3*(37).

Cachin, C. (2016, July). Architecture of the hyperledger blockchain fabric. In *Workshop on distributed cryptocurrencies and consensus ledgers* (Vol. 310, No. 4).

Cheng, J. C., Chen, W., Chen, K., & Wang, Q. (2020). Data-driven predictive maintenance planning framework for MEP components based on BIM and IoT using machine learning algorithms. *Automation in Construction*, *112*, 103087.

Dabbagh, M., Kakavand, M., Tahir, M., & Amphawan, A. (2020, September). Performance Analysis of Blockchain Platforms: Empirical Evaluation of Hyperledger Fabric and Ethereum. In *2020 IEEE 2nd International Conference on Artificial Intelligence in Engineering and Technology (IICAIET)* (pp. 1-6). IEEE.

Dave, B., Buda, A., Nurminen, A., & Främling, K. (2018). A framework for integrating BIM and IoT through open standards. *Automation in Construction*, *95*, 35-45.

Deng, Y., Gan, V. J., Das, M., Cheng, J. C., & Anumba, C. (2019). Integrating 4D BIM and GIS for construction supply chain management. *Journal of Construction Engineering and Management*, *145*(4), 04019016.

Gupta, S., Hellings, J., Rahnama, S., & Sadoghi, M. (2020). Building high throughput permissioned blockchain fabrics: challenges and opportunities. *Proceedings of the VLDB Endowment*, *13*(12), 3441-3444.

Helliar, C. V., Crawford, L., Rocca, L., Teodori, C., & Veneziani, M. (2020). Permissionless and permissioned blockchain diffusion. *International Journal of Information Management*, *54*, 102136.

Hijazi, A. A., Perera, S., Calheiros, R. N., & Alashwal, A. (2021). Rationale for the Integration of BIM and Blockchain for the Construction Supply Chain Data Delivery: A Systematic Literature Review and Validation through Focus Group. *Journal of Construction Engineering and Management*, *147*(10), 03121005.

Hsu, P. Y., Aurisicchio, M., & Angeloudis, P. (2019). Risk-averse supply chain for modular construction projects. *Automation in Construction*, *106*, 102898.

Hwang, B. G., Shan, M., & Looi, K. Y. (2018). Knowledge-based decision support system for prefabricated prefinished volumetric construction. *Automation in Construction*, *94*, 168-178.

Innella, Filomena, Mehrdad Arashpour, and Yu Bai. "Lean methodologies and techniques for modular construction: Chronological and critical review." *Journal of Construction Engineering and Management* 145.12 (2019): 04019076.

Kanan, R., Elhassan, O., & Bensalem, R. (2018). An IoT-based autonomous system for workers' safety in construction sites with real-time alarming, monitoring, and positioning strategies. *Automation in Construction*, *88*, 73-86.

Lee, D., Lee, S. H., Masoud, N., Krishnan, M. S., & Li, V. C. (2021). Integrated digital twin and blockchain framework to support accountable information sharing in construction projects. *Automation in construction*, *127*, 103688.

Li, C. Z., Xue, F., Li, X., Hong, J., & Shen, G. Q. (2018a). An Internet of Things-enabled BIM platform for on-site assembly services in prefabricated construction. *Automation in construction*, *89*, 146-161.

Li, C. Z., Chen, Z., Xue, F., Kong, X. T., Xiao, B., Lai, X., & Zhao, Y. (2020a). A blockchain-and IoT-based smart product-service system for the sustainability of prefabricated housing construction. *Journal of Cleaner Production*, *286*, 125391.

Li, S., Da Xu, L., & Zhao, S. (2018b). 5G Internet of Things: A survey. *Journal of Industrial Information Integration*, *10*, 1-9.

Li, X., Shen, G. Q., Wu, P., & Yue, T. (2019a). Integrating building information modeling and prefabrication housing production. *Automation in Construction*, *100*, 46-60.

Li, X., Wu, C., Wu, P., Xiang, L., Shen, G. Q., Vick, S., & Li, C. Z. (2019b). SWP-enabled constraints modeling for on-site assembly process of prefabrication housing production. *Journal of Cleaner Production*, *239*, 117991.

Li, X., Chi, H. L., Wu, P., & Shen, G. Q. (2020). Smart work packaging-enabled constraint-free path re-planning for tower crane in prefabricated products assembly process. *Advanced Engineering Informatics*, *43*, 101008.

Li, X., Wu, L., Zhao, R., Lu, W., & Xue, F. (2021). Two-layer Adaptive Blockchain-based Supervision model for off-site modular housing production. *Computers in Industry*, *128*, 103437.

Liu, G., Li, K., Zhao, D., & Mao, C. (2017). Business model innovation and its drivers in the Chinese construction industry during the shift to modular prefabrication. *Journal of Management in Engineering*, *33*(3), 04016051.

Liu, H., Sydora, C., Altaf, M. S., Han, S., & Al-Hussein, M. (2019). Towards sustainable construction: BIM-enabled design and planning of roof sheathing installation for prefabricated buildings. *Journal of Cleaner Production*, *235*, 1189-1201.

Lu, W.S., Li, X, Xue, F., Zhao, R., & Wu, L.P.F.(2021). Exploring Smart Construction Objects as Blockchain Oracles in Construction Supply Chain Management, *Automation in Construction, 129,*103816

Luo, L., Jin, X., Shen, G. Q., Wang, Y., Liang, X., Li, X., & Li, C. Z. (2020). Supply Chain Management for Prefabricated Building Projects in Hong Kong. *Journal of Management in Engineering*, *36*(2), 05020001.

MacLeamy, P. A. T. R. I. C. K. (2004). Collaboration, integrated information and the project lifecycle in building design, construction and operation. *WP-1202, The Construction Users Roundtable*.

Mazairac, W., & Beetz, J. (2013). BIMQL–An open query language for building information models. *Advanced Engineering Informatics*, *27*(4), 444-456.

Marzouk, M., & Abdelaty, A. (2014). Monitoring thermal comfort in subways using building information modeling. *Energy and Buildings*, *84*, 252-257.

Mekki, K., Bajic, E., Chaxel, F., & Meyer, F. (2018, March). Overview of cellular LPWAN technologies for IoT deployment: Sigfox, LoRaWAN, and NB-IoT. In *2018 IEEE international conference on pervasive computing and communications workshops* (pp. 197-202). IEEE.

Mentzer, J. T., DeWitt, W., Keebler, J. S., Min, S., Nix, N. W., Smith, C. D., & Zacharia, Z. G. (2001). Defining supply chain management. *Journal of Business Logistics*, *22*(2), 1-25.

Mohamed, A. G., Abdallah, M. R., & Marzouk, M. (2020). BIM and semantic web-based maintenance information for existing buildings. *Automation in Construction*, *116*, 103209.

Nakamoto, S. (2008). Bitcoin: A peer-to-peer electronic cash system.(2008).

NIBS, N. I. (2015). National BIM Standard-United States: https://www.nationalbimstandard.org/

Nguyen, G. T., & Kim, K. (2018). A Survey about Consensus Algorithms Used in Blockchain. *Journal of Information Processing Systems*, *14*(1).

Pongnumkul, S., Siripanpornchana, C., & Thajchayapong, S. (2017, July). Performance analysis of private blockchain platforms in varying workloads. In *2017 26th International Conference on Computer Communication and Networks (ICCCN)* (pp. 1-6). IEEE.

Qian, X. A., & Papadonikolaki, E. (2020). Shifting trust in construction supply chains through blockchain technology. *Engineering, Construction and Architectural Management*.

Ramaji, Issa J., and Ali M. Memari. (2016). Product architecture model for multistory modular buildings. *Journal of Construction Engineering and Management, 142* (10), 04016047.

Solihin, W., Eastman, C., Lee, Y. C., & Yang, D. H. (2017). A simplified relational database schema for the transformation of BIM data into a query-efficient and spatially enabled database. *Automation in Construction*, *84*, 367-383.

Tang, S., Shelden, D. R., Eastman, C. M., Pishdad-Bozorgi, P., & Gao, X. (2019). A review of building information modeling (BIM) and the internet of things (IoT) devices integration: Present status and future trends. *Automation in Construction*, *101*, 127-139.

Thai, H. T., Ngo, T., & Uy, B. (2020). A review on modular construction for high-rise buildings. *Structures*, 28,1265-1290.

Wang, Z., Wang, T., Hu, H., Gong, J., Ren, X., & Xiao, Q. (2020). Blockchain-based framework for improving supply chain traceability and information sharing in precast construction. *Automation in Construction*, *111*, 103063.

Xu, G., Li, M., Chen, C. H., & Wei, Y. (2018). Cloud asset-enabled integrated IoT platform for lean prefabricated construction. *Automation in Construction*, *93*, 123-134.

Xue, F., Chen, K., Lu, W., Niu, Y., & Huang, G. Q. (2018). Linking radio-frequency identification to Building Information Modeling: Status quo, development trajectory and guidelines for practitioners. *Automation in Construction*, *93*, 241-251.

Xue, F., & Lu, W. (2020). A semantic differential transaction approach to minimizing information redundancy for BIM and blockchain integration. *Automation in Construction*, *118*, 103270.

Yin, X., Liu, H., Chen, Y., & Al-Hussein, M. (2019). Building information modeling for off-site construction: Review and future directions. *Automation in Construction*, *101*, 72-91.

Zhai, Y., Chen, K., Zhou, J. X., Cao, J., Lyu, Z., Jin, X., ... & Huang, G. Q. (2019). An Internet of Things-enabled BIM platform for modular integrated construction: A case study in Hong Kong. *Advanced Engineering Informatics*, *42*, 100997.

Zhang, C., Zhou, G., Li, H., & Cao, Y. (2020). Manufacturing blockchain of things for the configuration of a data-and knowledge-driven digital twin manufacturing cell. *IEEE Internet of Things Journal*, *7*(12), 11884-11894.

Zhang, Z., Yuan, Z., Ni, G., Lin, H., & Lu, Y. (2020 b). The quality traceability system for prefabricated buildings using blockchain: An integrated framework. *Frontiers of Engineering Management*, *7*(4), 528-546.

Zheng, R., Jiang, J., Hao, X., Ren, W., Xiong, F., & Ren, Y. (2019). bcBIM: A blockchain-based big data model for BIM modification audit and provenance in mobile cloud. *Mathematical Problems in Engineering*, *2019*.

Zheng, Z., Xie, S., Dai, H., Chen, X., & Wang, H. (2017, June). An overview of blockchain technology: Architecture, consensus, and future trends. In *2017 IEEE International Congress on Big Data (BigData congress)* (pp. 557-564). IEEE.

Zhong, R. Y., Peng, Y., Xue, F., Fang, J., Zou, W., Luo, H., ... & Huang, G. Q. (2017). Prefabricated construction enabled by the Internet-of-Things. *Automation in Construction*, *76*, 59-70.

Zins, C. (2007). Conceptual approaches for defining data, information, and knowledge. *Journal of the American Society for Information Science and Technology*, *58*(4), 479-493.