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Two-layer Adaptive Blockchain-based Supervision Model for Off-site Modular Housing Production

Abstract

By manufacturing housing products off-site and assembling on-site, modular construction can significantly improve the housing supply efficiency, particularly for high-density cities. However, off-site modular housing production (OMHP) supervision is currently problematic. The production parties are reluctant to provide detailed private data; Even worse, the submitted operation records can be easily fabricated, tampered with, or hard to trace the responsibility. This study develops an innovative Two-layer Adaptive Blockchain-based Supervision (TABS) model for OMHP. The first layer includes the adaptive private sidechains of participants. The second layer is the main blockchain for communication and 'trading' among all participants. Benefitted from the unique adaptive two-layer structure, TABS can avoid tampering with operation records by the main blockchain and drive the participants to publish their operation records promptly without privacy leaks. A system prototype was also developed to evaluate the performance of the TABS model. The results indicated that the TABS model could enhance privacy and reduce storage costs at an acceptable latency level. This study's findings can pave the avenue for a tamper-proof and privacy-preserving supervision mechanism in the architecture, engineering, and construction industry.

Keywords: Two-layer adaptive blockchain; Off-site construction; Modular construction; Production and quality inspection

1. Introduction

The construction industry will continue to be one of the main driving forces leading the economic recovery and social development after the coronavirus lockdown (Stefani and Coulton, 2020; Tapsfield, 2020). With contact-restrict in the pandemic, modular construction involving less labor is an innovative approach that employs freestanding volumetric modules manufactured off-site and then transported to a construction site for assembly (Gao et al., 2020). As the most value-added process of modular construction, off-site modular housing production (OMHP) involves various materials, participants, and steps.

However, there are several practical concerns with quality assurance in factories for OMHP. For example, there is usually a lack of real-time progress information and plan display in the production preparation stage (Li et al., 2019). When entering productions, the absence of systematic records of operations (e.g., structure works, electrical and mechanic works, testing, and commissions) aroused construction stakeholders' attention (Xu et al., 2020). Manual recording (e.g., progress and inspection records) often leads to input errors, file loss, and even data manipulation during the production inspection (Zhong et al., 2020). All the issues mentioned above in the OMHP significantly hinder supervision. These issues can be further deteriorated in Hong Kong, mainly due to the coronavirus pandemic. As the high construction costs, aging problems, and labor shortages, the construction industry in Hong Kong outsources OMHP to the factories in nearby Guangdong Province, Mainland China. The cross-border supervision of OMHP has become a conundrum due to the travel restrictions during the coronavirus pandemic. Thus, there is an urgent need for technologies to build trust and promise OMHP information's authenticity.

Blockchain, emerging from the technology sphere recently, promises to provide the desired strategy to build trust in the industry. A blockchain refers to a cryptographically immutable distributed database within a decentralized consensus mechanism (Risius and Spohrer 2017). From the Institution of Civil Engineers, Penzes et al. (2018) reported blockchain technology promises, such as augmented transparency, boosted traceability, enhanced immutability, increased decentralization, improved privacy, and extended smartness. Many scholars are actively studying blockchain applications in construction: integration of Building Information Modeling (BIM) and blockchain (Xue and Lu, 2020), construction business processes (Yang et al., 2020), transaction automation with smart contracts (Hamledari and Fisher, 2020), payment in construction projects (Das et al., 2020), and immutable records of transactions, assets, and ownership (Zhong et al., 2020).

A growing number of blockchain studies on the supply chain and information management for OMHP has also gained attention recently. These studies focused on supply chain traceability and quality management. For example, Wang et al. (2020) proposed a blockchain-based framework for improving supply chain traceability and information sharing. Similarly, Zhang et al. (2020) developed a quality traceability system for building components based on blockchain. Zhong et al. (2020) and Sheng et al. (2020) proposed blockchain prototypes for construction quality information management. Nevertheless, the construction companies naturally wish to keep their business data private and, therefore, reluctant to make data accessible to all participants. Moreover, migrating historical data of all processes stored in traditional systems to the chain will cause high costs and require larger storage space. Thus, previous studies have not developed a sound solution to supervise each operation in OMHP while protecting related enterprises' data privacy.

This paper aims to present a novel blockchain-based supervision model to enhance the supervision of OMHP. This research has three specific objectives:

1) to review and comb the current business process of OMHP;

2) to develop a two-layer adaptive blockchain-based supervision (TABS) model for off-site modular housing production; and
3) to analyze the performance of the TABS model by developing a prototype system.

The rest of this paper is organized as follows. Section 2 reviews and combs the current business process of OMHP. Section 3 is a literature review of blockchain technology. Section 4 presents the details of TABS. Section 5 analyzes the performance of the TABS model. Section 6 offers our discussion, and Section 7 concludes this research.

2. Problem Statement

The current practice of OMHP in factories generally has three sub-processes, i.e., production preparation, production, and inspection. The scope of the OMHP process has been identified as follows:

1) the entry criteria are that the project manager signs the contract to confirm the production;
2) the input is the master plan and the design drawings;
3) the exit criteria are that the project manager confirms the delivery order; and
4) the output is the quality assured modular housing products.

As shown in Fig. 1(a), the contractor coordinates with subcontractors and manufacturers to propose the production plan after placing an order. The manufacturer's design department develops detailed production shop drawings after the confirmation of design drawings. Once the production shop drawings are ready, they should be approved by the contractor and owner. Upon approval, the manufacturer can make an overall production plan. The material list will be made based on the production execution plan. The order of 2D panels, rebar, and other material will be sent to the supplier by the manufacturer's procurement department. These materials will be inspected and only be used if they pass the inspections and tests. For example, in the rebar inspection, results with the color are marked on the rebar. Green means the rebar passes the inspection, yellow means unchecked, and red means disqualification. After inspection, materials will be transported to the factory. The production department will organize the production if required material ready.

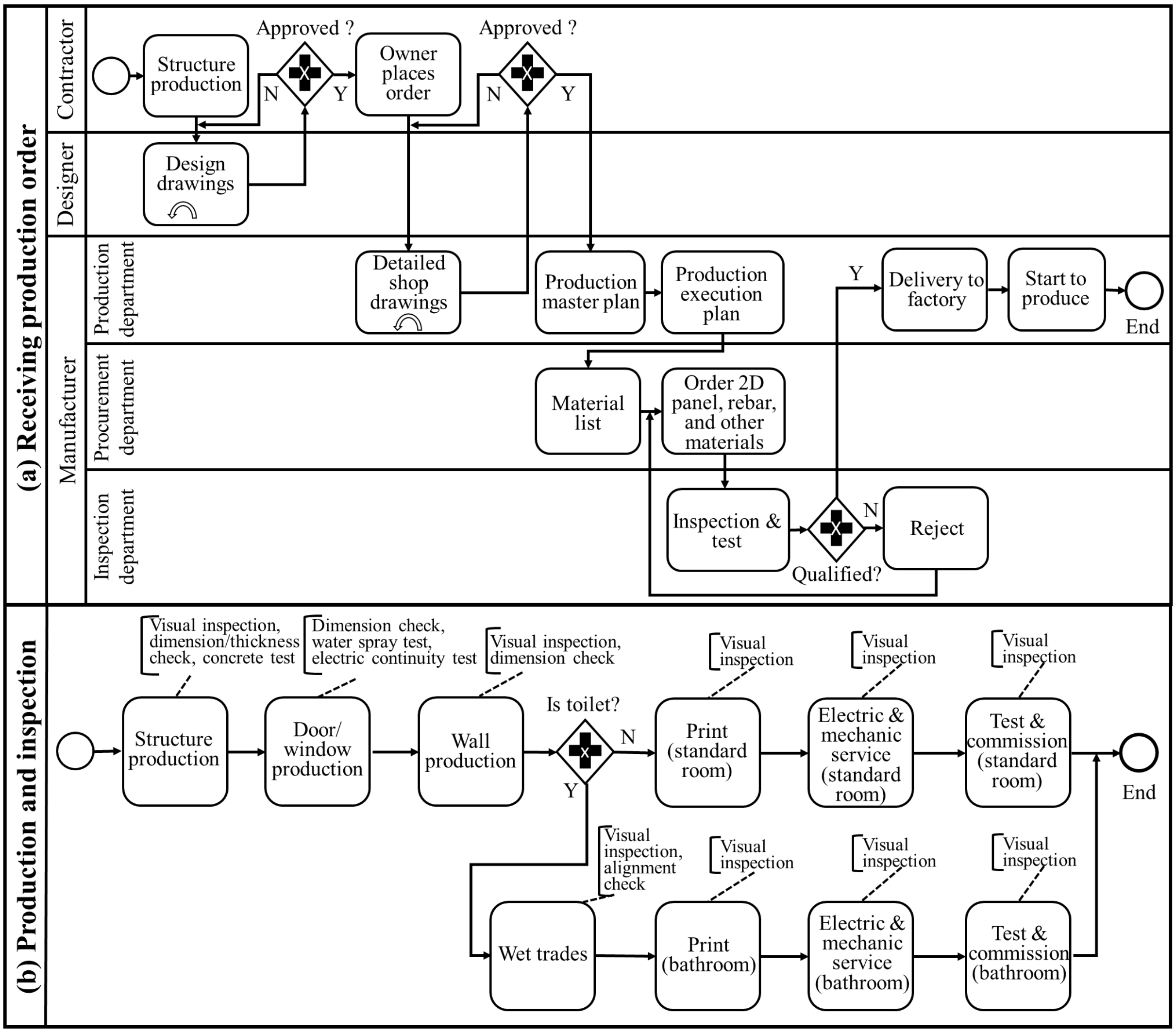

Figure 1. The business process of off-site modular housing production (Source: Authors). (a) Production preparation; (b) MiC standard room and bathroom production and inspection

Fig. 1(b) shows that the standard modular room is produced by following a sequential procedure from the structure, door/window, wall, print, electrical & mechanic service to test & commission. Numerous inspection and test methods are involved for quality control and quality assurance in each hold point and witness point. For example, the check of hot-dip galvanized thickness, cladding sub-frame alignment, dimension, and water test for chassis enclosure are conducted in 3D assembly welding of structure production. Several processes are adjusted for the toilet module, such as the wet trades (e.g., bathroom wall and floor tiles installation, waterproof layer, and flood test) are involved.

Blockchain has several advantages that may address the issues in the current business process of OMPH for supervising the information of material, production, and inspection:

- **Transparency:** Current records may not be available to all stakeholders. Blockchain can require confirmation from all parties.
- **Traceability:** Current records may not be tracked in the whole OMHP process. Blockchain can provide the status of modular housing products with a timestamp.
- **Immutability:** Current records can be modified without rigorous supervision. Blockchain can offer a tamper-proof solution.
- **Decentralization:** Current records are managed in a centralized manner. Blockchain can prevent them entirely controlled by one party.
- **Privacy-preserve:** Current records may involve privacy issues. Blockchain can encrypt them by using hashing algorithms.
- **Smartness:** smart contracts facilitate the automatic execution process in transparency, traceability, immutability, decentralization, and privacy.

3. Literature Review

3.1 Blockchain Technology

Blockchain is supported by three core components: cryptography, consensus mechanisms, and distributed storage (Crosby et al., 2018). Hash algorithms and Merkle trees are typical in cryptography, ensuring that the data cannot be tampered with (Kosba et al., 2016). In the blockchain, transaction data can be bundled into blocks, as shown in Fig. 2, and each block is a package data structure containing headers and transaction data (Nakamoto, 2008; Gupta, 2017). The header contains metadata, including index, previous block hash, current block hash, nonce, timestamp, and Merkle root. Blocks are connected in sequence, starting with the genesis block. Hashing sequentially interlinked blocks implies that the verified transaction data is adopted as input to a hash algorithm that converts the data into a fixed-length string. As each data in the block is hashed, then united and hashed again, this process creates the Merkle tree and the final root hash. A hash value of a block can be regarded as a unique digest of the current block data. The previous block hash in the current block is used to enable the blocks to build a chain. Thus, any small alteration to data, hash values in the entire chain need to be altered.

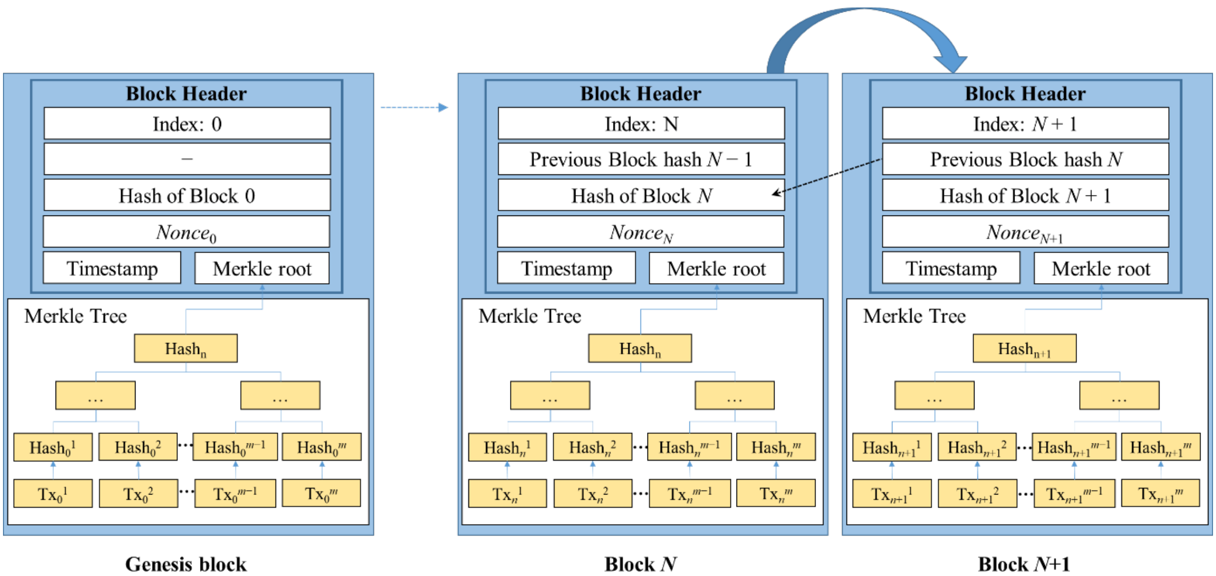

Figure 2. An example of a blockchain (Adapted from Nakamoto (2008))

Consensus mechanisms are protocols for endorsing the order and correctness of data (Cachin and Vukolić, 2017). Only when a consensus is reached can transaction data be added to the blockchain as a new block. There are many consensus algorithms, among which the five most common are: Proof of Authority (PoA), Proof of Work (PoW), Proof of Stake (PoS), Delegated Proof of Stake (DPoS), and Practical Byzantine Fault Tolerance (PBFT) (Xiao et al., 2020).

The distributed data storage of blockchain, principally constituted by ledgers, is realized through a decentralized network (Perera et al., 2020). The word “distributed” means that ledgers are scattered in many places in a shared manner to log transaction data. Nodes are network participants who hold copies of the ledger and/or execute smart contracts to query from or submit transactions to ledgers. Together, these components promise that the status of tangible assets or intangible events to be endorsed, stored, and shared with the smallest chance of tampering. Simply put, blockchain stores immutable, verifiable, and transparent information.

Smart contracts are digital contracts that can self-execute when preset conditions are met (Luu et al., 2016). Smart contract scripts can indicate a blockchain’s maturity level at 2.0 or above (Angelis and da Silva, 2019). Once the smart contract is successfully installed in the blockchain network, no one can change the execution rules. Smart contracts can continuously monitor data changes on the blockchain or external data sources and automatically respond when conditions are met. Therefore, smart contracts can help disintermediation (e.g., banks), thereby reducing related costs and shifting normative trust (e.g., trust in people) to naturalistic trust (e.g., trust in coding). Fig. 3 shows the structure of smart contracts. A smart contract contains two key components: preset conditions and actions that need to be carried out when the preset conditions are met. Smart contracts can digitize and automate business processes, allowing the development of blockchain 3.0 decentralized applications (DApps) (Christidis and Devetsikiotis, 2016; Angelis and da Silva, 2019).

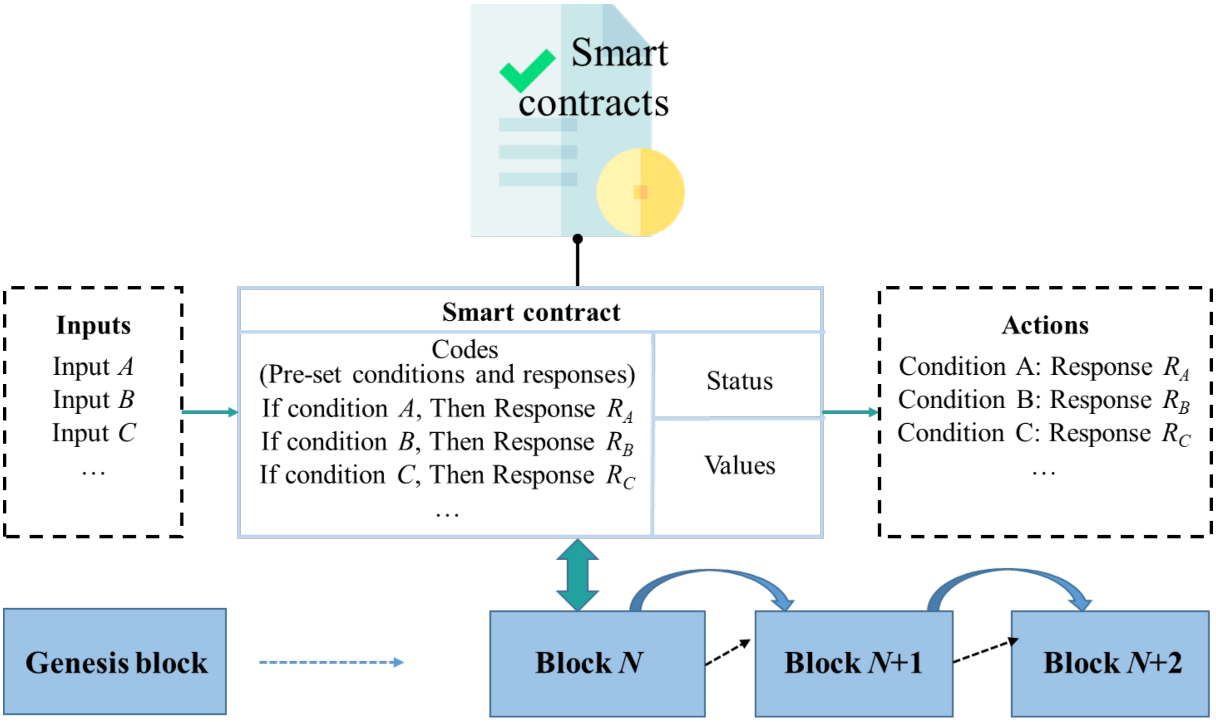

Figure 3. Schematic of the smart contract (Adapted from Bragagnolo et al. (2014))

3.2 Blockchains in the Construction Industry

Although many industries have developed different blockchain prototypes and applications, the construction industry is only in the initial stage of blockchain implementation. The loosely-coupled and project-based structures in the construction industry (Dubois and Gadde, 2002) require numerous stakeholders to communicate over time with various incentives. These structures' nature brings coordination difficulties such as lack of trust, poor information exchange, and fragmented system records (Hunhevicz and Hall, 2020). Theoretically, the promises of secured transactions that blockchain can give are in line with these coordination difficulties. Even so, there are few implementations of blockchain in construction. Instead, most literature to date provides a sketch of the potential use cases for blockchain in construction. For instance, early literature views the prospect of blockchain as a supplementary technology to BIM and Internet of Thing (IoT) (Mathews et al., 2017) because BIM and IoT are again limited by problems of trust and liability encountered throughout the industry. Therefore, Ye et al. (2018) suggested using blockchain to store data generated by IoT in a transparent and safe environment and BIM as a tool for digital processing construction project data. DeLa Peña and Papadonikolaki (2019) proposed that using the blockchain as an immutable ledger, the combination of blockchain and IoT can build trust among construction companies.

Starting in 2017, many researchers and consulting firms have identified potential use case scenarios to employ blockchain in construction. Hunhevicz and Hall (2020) noted that the construction industry's potential blockchain use cases mainly include seven categories. Blockchain can help notarize and synchronize documents in the construction administration process (Wang et al., 2017). Combined with smart contracts, blockchain can realize transaction automation for payment (Hamledari and Fisher, 2020), business process and information integration (Yang et al., 2020), and compliance checking (Nawari and Ravindran, 2019). Also, blockchain can be used as immutable track-records, for example, to record BIM changes (Xue and Lu, 2020), and track supply chain, project progress, and worked hours (Wang et al., 2020). Similarly, blockchain can record assets and ownership (Raslan et al., 2020). Das et al. (2020) reported the use of blockchain cryptocurrency for payment and incentive schemes. In summary, blockchain does bring exciting opportunities to the construction industry. However, the use cases of using blockchain to supervise OMHP are largely unexplored.

3.3 Blockchains for Production Supervision

In literature, a few studies using blockchain technology have been observed for production supervision. Peng et al. (2020) showed that vaccine production records could be protected from tampering through an effective double-level blockchain method while maintaining enterprises' privacy. Yong et al. (2020) demonstrated a "vaccine blockchain", organizing production inspection records into a hash table structure with timestamps to achieve traceability, security, and trust. In the food industry, Tao et al. (2019) proposed a food safety supervision system based on a hierarchical multi-domain blockchain network with a secondary-check mechanism. Liang et al. (2020) designed a blockchain system architecture to supervise the production safety of special equipment (e.g., pressure vessels and elevators) and record the corresponding producers' responsibilities. Blockchain-based supervision also covers the production quality management of textiles (ElMessiry and ElMessiry, 2018), agricultural products (Wang, 2019), and energy (Ferrag and Maglaras, 2019).

Many solutions have been provided to strengthen the supervision of the OMHP. Relying on quality assurance schemes and regulations, Hong Kong's Buildings Department requires authorized personnel and registered structural engineers to assign their respective quality control teams to supervise OMHP in assembly factories (BD, 2017). Technology adoption is also an essential strategic research field for OMHP supervision. BIM, as a digital representation of a facility's physical and functional characteristics and a shared knowledge resource for information (Li et al., 2017), is commonly utilized for production planning and management (Lu et al., 2020; Li et al., 2020). Progress and quality assurance of OMHP are also focused on the IoT, a networked interconnection of everyday objects, often equipped with ubiquitous intelligence via embedded systems (Li et al., 2018). Through integration with the BIM and enterprise resource planning system, IoT can enhance visualization and manage production processes, thereby enabling communication and collaboration between all parties (Razkenari et al., 2020). Nevertheless, merely relying on BIM, IoT, or traditional information management systems is not enough to truly achieve trust. These technologies are susceptible to a single point of failure and cybersecurity issues, which blur the responsibility level between different participants (Zhai et al., 2019). For example, the shared cloud BIM model and its data can be tampered with without tracing the responsibility of changes, and IoT sensors (e.g., RFID, GPS) may suddenly run out of power or report noises to reduce the quality of data.

In construction, especially OMHP, only minimal studies have focused on the uses of blockchains to supervise production. To improve the transparency of information between steel production companies, logistics, and consumers, and eliminate the security issues of existing IoT platforms, Cao et al. (2019) claimed a quality traceability system based on blockchain. Zhang et al. (2020) proposed a blockchain-based quality traceability system to ensure the components' quality in production, transportation, and construction. It is found that more research has focused on the use of blockchain to improve the traceability of the construction supply chain (e.g., Wang et al., 2020; Zhang et al., 2020) and the overall management of information (e.g., Sheng et al., 2020; Zhong et al., 2020).

Nevertheless, once OMHP has flaws in the production process, it is almost impossible to prevent inferior housing products from reaching consumers. Besides, due to high technical, learning, and training costs, it is not feasible to completely replace the existing information system with a blockchain. Privacy is another major issue when implementing blockchain in production, as producers and related enterprises wish to keep design data and plan internally. In short, the existing blockchain studies have not given in-depth investigations on OMHP supervision, nor have they provided sufficient consideration for the privacy protection of production data and effective data storage. With the harness of these capacities in blockchain, the supervision process of OMPH can be enhanced. Thus, this study proposes a model to explain how to realize the off-site production supervision for quality assurance, progress, and cost efficiency.

4. The Two-layer Adaptive Blockchain-based Supervision Model for OMHP

This section presents a novel Two-layer Adaptive Blockchain-based Supervision (TABS) model for resolving the supervision and privacy problems encountered in OMHP. As shown in Fig. 4, four main participants, i.e., supplier, manufacturer, contractor, and owner, are involved in TABS for the OMHP business process. Suppliers first deliver the 2D panel, rebar, and other material to the OMHP factory by the manufacturer's orders. Next, the manufacturer will schedule the production and execute it according to the due time. The contractor will also organize the inspection and test activities for each production process in every hold and witness point. The project owner can supervise and monitor the whole process via the timely information in the OMHP processes, including material information, production information, inspection information, and supervision information. Material information includes data for material ID, production, and inspection results. Production information records the detailed production processes of modular products. Inspection information contains detailed inspection and test results of each hold and witness point. Supervision information comprises primary information of material, production, and inspection for each modular product.

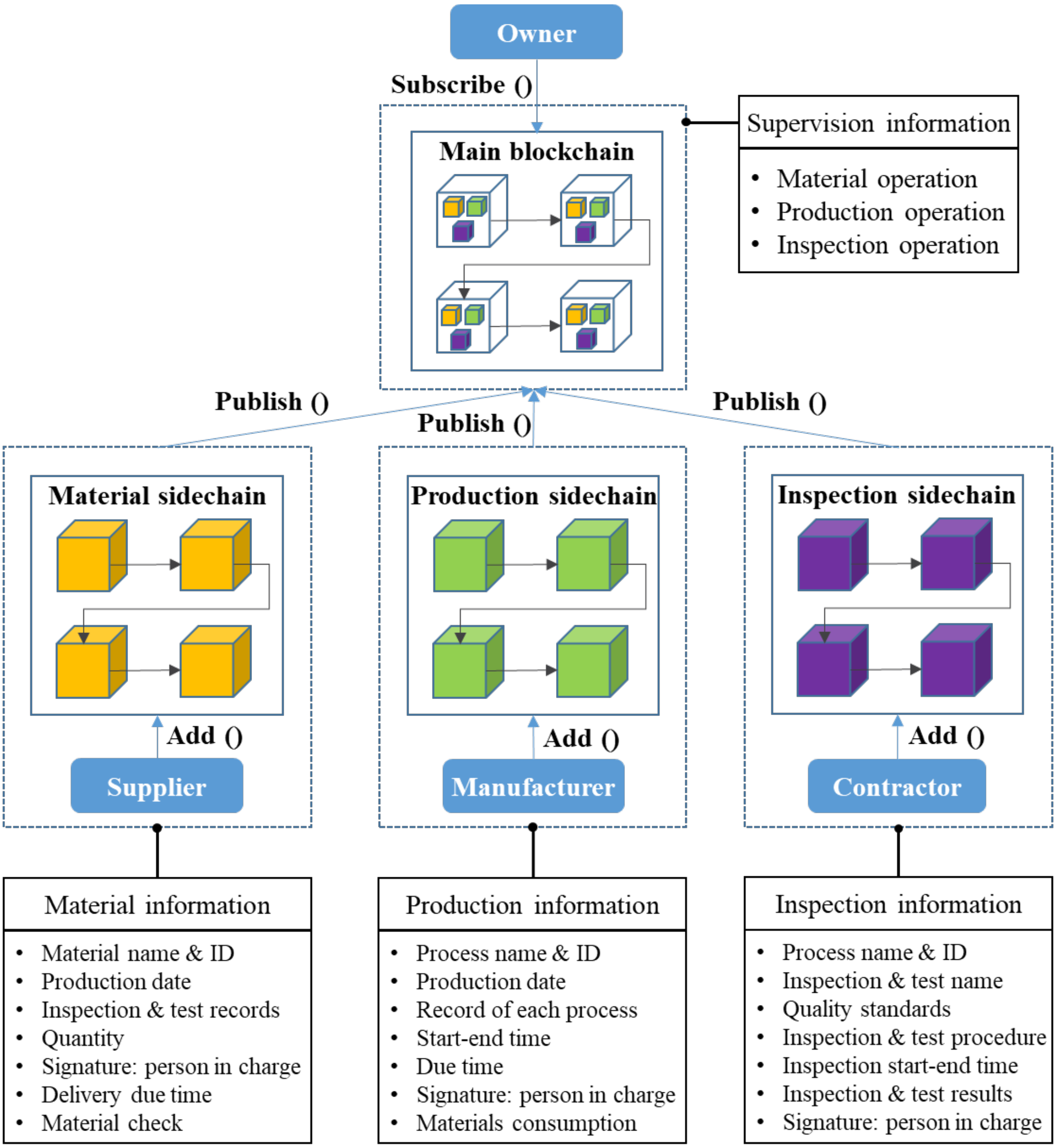

Figure 4. Two-layer adaptive blockchain-based supervision (TABS) model for OMHP

(Source: Authors)

In the actual supervision process, the responsibilities of quality defects, production delays, and cost overrun are not easily determined. TABS model allows each participant to access the status and records of material supply, production, and inspection with preserving the data privacy of material supplier, manufacturer, and contractor. Four participants are involved in the main blockchain. Each participant receives a copy of the main blockchain, facilitating them to supervise each transaction. In the main blockchain, each transaction indicates an operation, such as delivery 2D panel, structure production, concrete test, window/door production, and dimension check. An operation can be verified when all participants agree on its authenticity by reaching a consensus. The operations are stored in the supplier, manufacturer, and contractor's sidechains and retrieved via the main blockchain's smart contracts. The self-execution functions are embedded in smart contracts that can be triggered by the owner. The details of the TABS model are illustrated in the following sections.

4.1 Two-Layer Adaptive Blockchain Structure

The key to OMHP supervision is monitoring the authentic OMHP operations in the entire process, and the blockchain structure can directly affect supervision performance. However, in the traditional blockchain structure, there are two limitations to OMHP supervision. Firstly, the OMHP participants wish to keep their business data private and may be reluctant to make data accessible to all participants. In addition, there is a conflict between full backup and storage capacity in traditional blockchain for massive operation-oriented OMHP. Thus, the TABS model adopts a two-layer adaptive blockchain structure, including mainchain and sidechain (See Fig. 4). OMHP process has numerous operations, which may vary in different modular products, such as standard rooms and toilets. Each operation can be treated as a transaction. Each transaction holds the detailed data of the operation. Thus, a particular modular product's specific operation can be matched to a specific transaction. The design of mapping operation with transaction ensures the two-layer adaptive blockchain structure can handle various modular products produced by different operations.

Private operation transactions can be stored in each participant's sidechain, and other participants in the main blockchain can not access it. The private transaction structure can be shown in Fig. 5. Each transaction includes a timestamp (transaction time), the signature of the person in charge, the hash, the previous hash (previous operation), and the data. The data are formed as a hash table, a dictionary-like data structure with unique keys and values. These hash tables' keys present the operation categories, including "material," "production," and "inspection." These hash tables' values show in the form of an object containing the content of data, such as inspection operation, inspection time. With the data frame structure, the operation transactions can be format-free when uploaded into the sidechain. The sidechain layer consists of the material supply, module production, and inspection. These three sidechains are maintained by the supplier, manufacturer, and contractor, which can not only provide authentic operations and but also ensure their data privacy by using hashing data.

Timestamp	Signature	Hash	Previous hash	Data = {"Material": material operation, completion time}

Figure 5. Data frame structure in the sidechain (Source: Authors)

Each block in the main blockchain comprises two parts: header and transactions. Block header mainly consists of the index (block number in the chain), timestamp, the signature of the supplier, manufacturer, contractor, owner, the hash value of the current the previous block. There are three types of transactions retrieved from the sidechains of the supplier, manufacturer, and contractor, as shown in Fig. 6. The project owner can access OMHP operation records from the main blockchain, and smart contracts are deployed into the main blockchain, subscribe to the operation records from the sidechain, which can publish the operation records at a specific time period for modular product supervision. Compared with the traditional blockchain structure, the two-layer adaptive blockchain structure has significant advantages in cross-participant data privacy and flatten supervision.

The adaptability of this blockchain structure can be reflected in two perspectives. First, the sidechains layer can be adaptive to full life cycle stakeholders of modular housing products, such as designers, logistics companies, and property management companies, to record information on design, transportation, and facility management. Second, the main blockchain layer can be extended to government and industry regulators and even can go public.

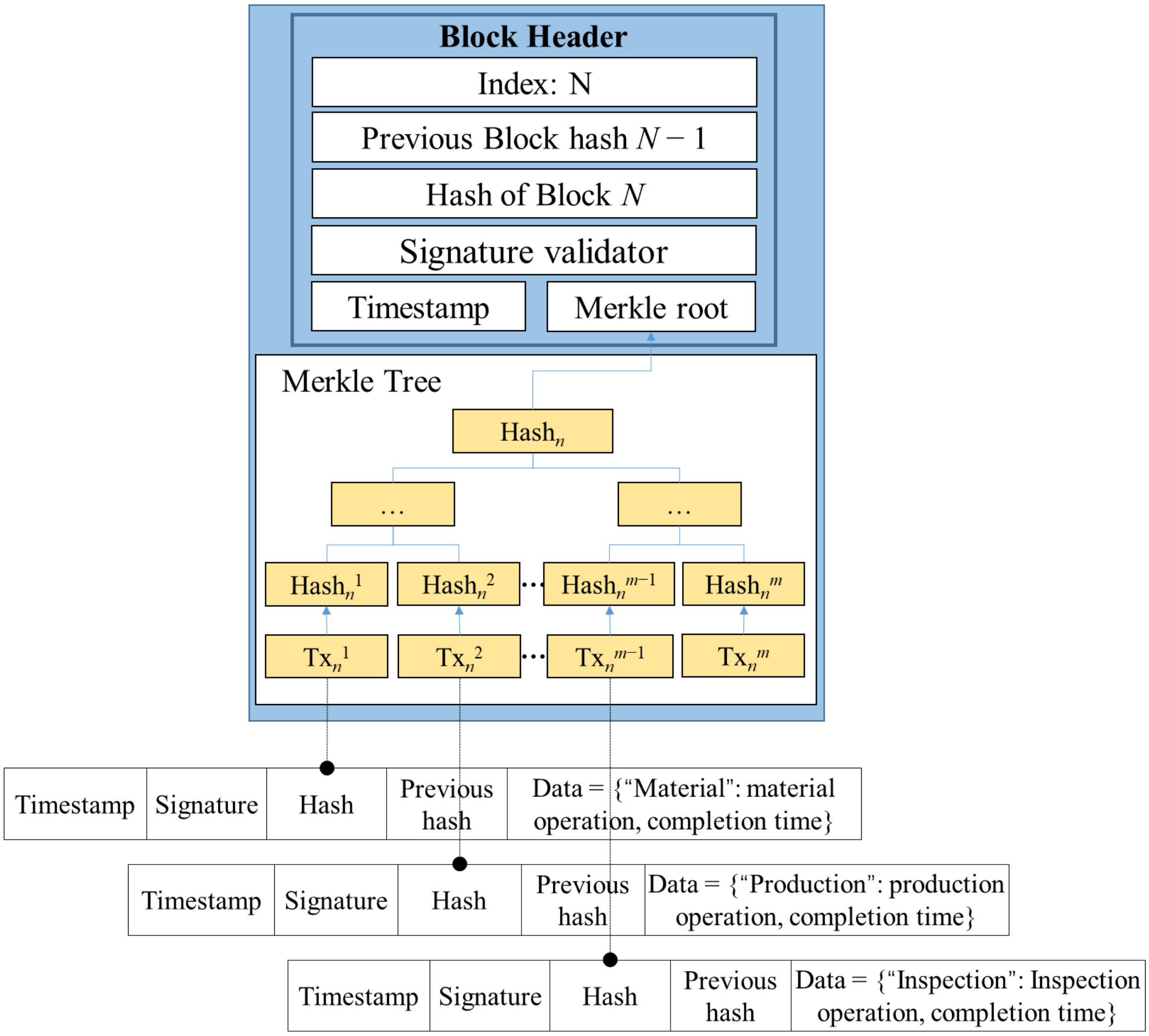

Figure 6. Block data structure in the main blockchain (Source: Authors)

4.2 Supervision Processes in Two-Layer Adaptive Blockchain Structure

Once disputes, e.g., quality defects, delays, or cost overrun, occur, the TABS model can help trace whether the qualified material is manufactured in rigorous production processes with timely progress and consistent inspection. Similar functions can help conduct random checks of material supply, production, and inspection. The TABS model employs a consortium blockchain architecture for the main blockchain to enable OMHP supervision in a publish-subscribe manner. The supervision process includes registration, publish-subscribe, ordering, and consensus. Fig. 7 demonstrates the detailed supervision processes in the TABS.

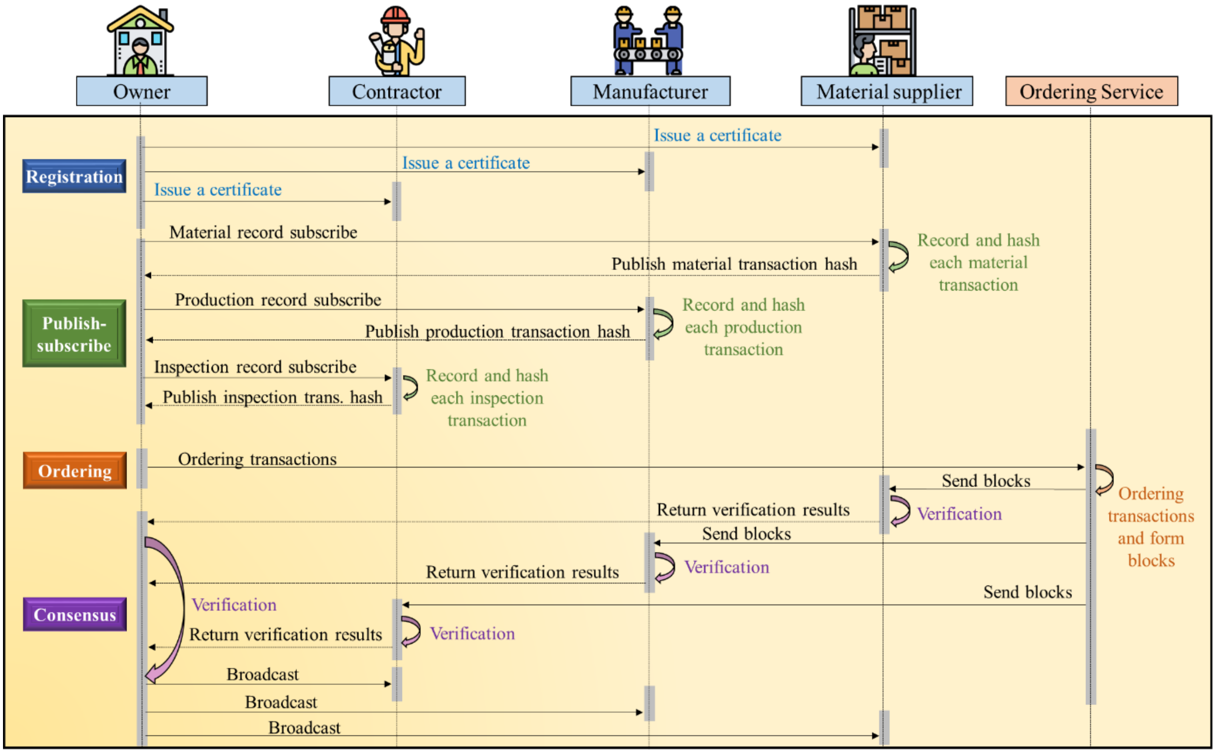

Figure 7. Sequence diagram of interactions in TABS (Source: Authors)

4.2.1 Registration

The participants' identities should be verified through their registration request to the owner. The owner holds the certificate authority and then issue certificates for each participant to join the main blockchain. The registration process offers both authority and privacy to participants, and a participant without registration cannot participate in the sequent processes of publish-subscribe and consensus. After registration, the participants can get an enrollment certificate (e.g., ID) and a transaction certificate for signatures.

4.2.2 Publish-subscribe

The publish-subscribe mechanism is adopted to generate the transaction flow proactively. For example, the owner can subscribe to the supplier's material record when the supplier starts to deliver the material to the manufacturer. And the supplier records and hashes each operation in its sidechain. The supplier then publishes the transaction hash to the owner, protecting the supplier's data privacy. Following the same mechanism, the owner can establish this publish-subscribe interaction patterns with the manufacturer and contractor in the off-site production stage.

4.2.3 Ordering Service

The owner serves as the ordering node (leader), receives transactions from different participants, and conducts the ordering service to form an ordered blockchain. All transactions from participants during a specific period are ordered. The ordering service can order transactions in sequence and packages them into new blocks. However, the ordering service cannot access the data in these transactions and has no permission to update the unverified block to each participant. It can only send the ordered blocks consecutively to the participants for verification. Once participants received the blocks ordered by the owner, they can evaluate whether these blocks are in the right sequence by checking the current block's hash value and the previous block's hash value.

4.2.4 Consensus Mechanism

All participants in the main blockchain can verify the authenticity of transactions in their received blocks. Each participant can determine whether it is valid or not by signing in the block and holding the copy of the data on-chain. All transactions can be saved in the blocks, even though they are not authentic. However, only verified transactions could be broadcast and updated in each participant's copy. For example, suppose the concrete test in inspection operation is verified. In that case, the status of this related modular product (e.g., modular standard room MSR0001) in the world state can be updated to "concrete test qualified," and the inspection time is also saved. If a participant does not receive an updated blockchain or stores an inaccurate copy of the blocks, it can link to the owner and then download the right one. To facilitate the verification results from each participant reaching a consensus, the PBFT is used as the consensus protocol (Castro et al., 1999). Compared with the Crash Fault Tolerant (CFT), which is typically used in the consortium blockchain, PBFT can not only tolerate failures of ordering nodes but also withstand malicious participants (Sousa et al., 2018). In TABS, it can tolerate one malicious participant (f) as there are four participants ($n = 4$) in total, given $f = (n - 1) / 3$. Typically, the owner is suggested to make several copies of the blockchain in the owner's sidechain for recovering from failures of the owner's node, such as the loss of data. Under this situation, the main blockchain owner can interact with its sidechain to request a consistent copy of the blockchain.

4.3 Smart Contracts for OMHP Supervision

Smart contracts in TABS allow encrypted data shared across the different participants, both on-chain and cross-chain. The business logic of publish-subscribe in TABS is a cross-chain interaction shown in Algorithm A.1 in Appendix. For example, the main blockchain owner can generate a hash as a start signal to the manufacturer for subscribing to each operation data of the production process. It then triggers the cross-chain interactions between the main blockchain and sidechain of the manufacturer to store operation data, generates transactions in the sidechain, and finally publish the transactions from the sidechain to the owner via the main blockchain.

The smart contracts for ordering and verification are conducted on the main blockchain (See Algorithm A.2 in Appendix). For example, the owner gets and orders transactions by recognizing the previous hash in each transaction. The owner creates the blocks and checks the production operation data provided by the manufacturer. They also need to hash the submitted data and check whether it is identical to the block's transaction hash. Then the owner broadcast the blocks to the participants for their further verification and signature. If all signatures are successful, the owner can update the blocks to all participants' copies of blockchain data.

5. Performance Analysis of the TABS

This section presents the performance analysis of the TABS model through a case study. HKU Wong Chuk Hang Students Residence is a representative modular construction project in Hong Kong, including two 17-story student residence tower buildings on top of a 3-story podium structure. A total of 1,224 modular products (e.g., room and toilet) will be transported from Foshan, Mainland China, to Hong Kong island for assembly. A prototype system is developed, and the related evaluation is conducted based on this case study.

5.1 Prototype and Experimental Settings

The TABS model was implemented on *Hyperledger Fabric* (version 2.2), and Javascript was used for writing the smart contracts in the chaincode. The development environment was in Ubuntu 18.04, and compared with virtual machines, docker with isolated containers use fewer resources can facilitate system prototype development. In the prototype, four participants are involved: (1) the owner, who serves as the orderer in the ordering service; (2) the contractor; (3) the manufacturer; (4) the supplier. Fig. 8 (a) presents the configuration information for these participants, and cryptogen in *Hyperledger Fabric* is used to facilitate the registration process by issuing the certificates, such as admincert (for each participant's administrator), cacert (for the owner), and tlscacert (for establishing connections), which can be seen in Fig. 8(b).

Each participant in Fig. 8(a) has an administrator registered in both the main blockchain and sidechain. The participants can receive certificates and public-private key from the Fabric CA module of the main blockchain. The administrator can also send requests to the Fabric CA of the sidechain for offering certificates and the public-private key to operators in the affiliated organization, which is responsible for adding operation records in the sidechain. The main blockchain's genesis block is configured, including information of ordering service, consortium, and each participant (See Fig. 8(c)). An anchor peer is devised in each participant for cross-participant communication in the main blockchain and cross-chain interactions between the main blockchain and sidechain (See Fig. 8(d)). Also, the *Hyperledger Explorer* can provide the visual details of the main blockchain. As shown in Fig. 9, graphical interfaces of *Hyperledger Explorer* list the detailed network composition, participants information, block, and certificate details.

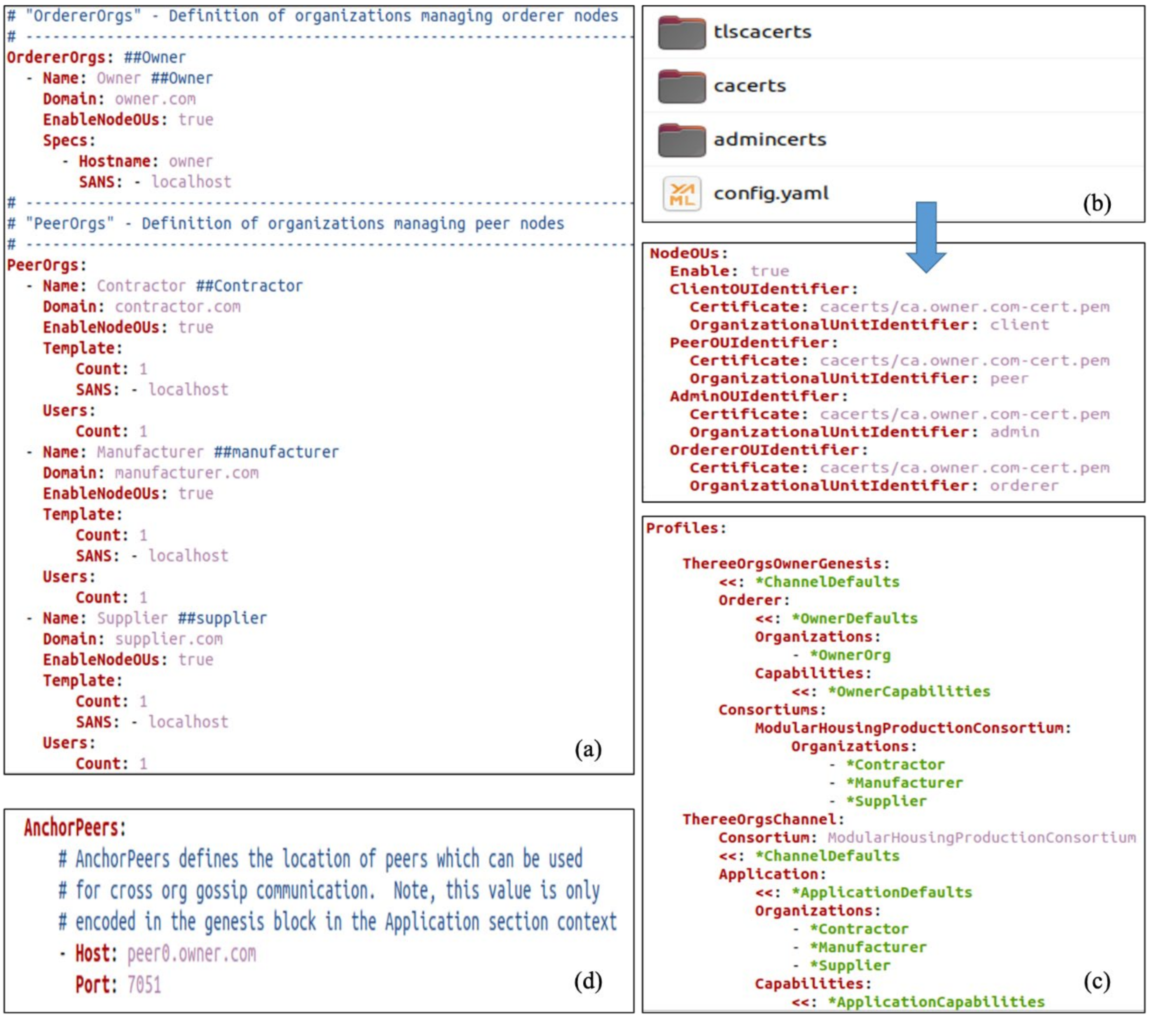

Figure 8. System configuration for: (a) participant; (b) certificate; (c) genesis block; and (d) anchor peer (Source: Authors)

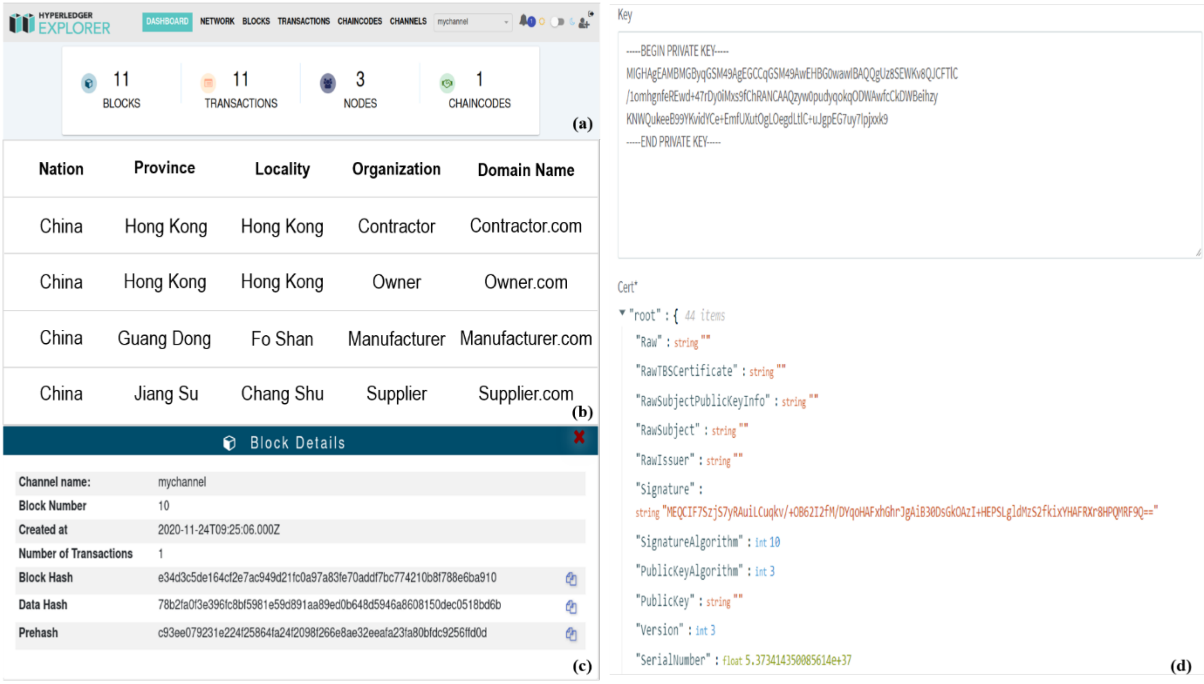

Figure 9. Main blockchain details. (a) network details; (b) participant details; (c) block details; and (d) certificate details (owner) (Source: Authors)

We developed the backend and frontend prototypes, including frameworks, tools, and components, as shown in Fig. 10, for each participant using *SpringBoot* (ver. 2.4.0) and *AdminLTE* (ver. 3). SpringBoot is a Java-based backend framework for developing web server and MySQL. AdminLTE is a bootstrap-based frontend framework that provides responsive, reusable, and commonly used components for fast development. Fig. 11 (a) and (b) show the prototype's interfaces for operation data publishing and subscribing. For example, when reaching the concrete cube test's inspection operation after the production operation of rebar fixing and pouring concrete, the test report with the inspection details and responsibilities must be uploaded to the contractor's sidechain as shown in Fig. 11 (a). The test report can be transformed into the JavaScript Object Notation (JSON) files by the JSON form plug-in and saved in the sidechain, and then it will be hashed and published to the owner in the main blockchain. After publishing the transaction and obtaining the consensus from each participant in the main blockchain, the operation of the concrete cube test is updated into the latest block.

The subscribing interface shows that each sidechain's historical operations can be traced, as shown in Fig. 11 (b). Moreover, the corresponding block details can also be seen on the main blockchain by clicking one of the transactions. These details include an index, timestamp, the participants' signatures, the hash value of the current and the previous block. After the operator uploads the operation data to the sidechain, the sidechain's backend will interact with the chaincode in the main blockchain. The chaincode verifies the signature and checks the hash before it can be published to the main blockchain.

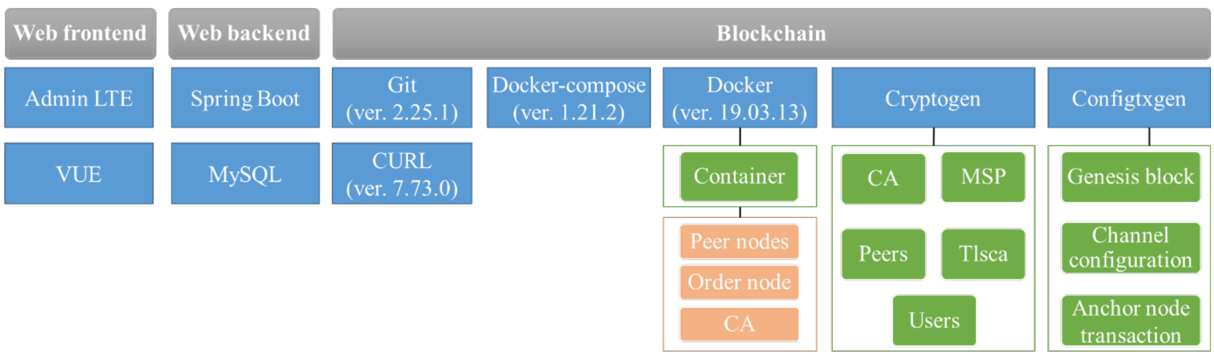

Figure 10. Frameworks, tools, and components involved in this prototype development

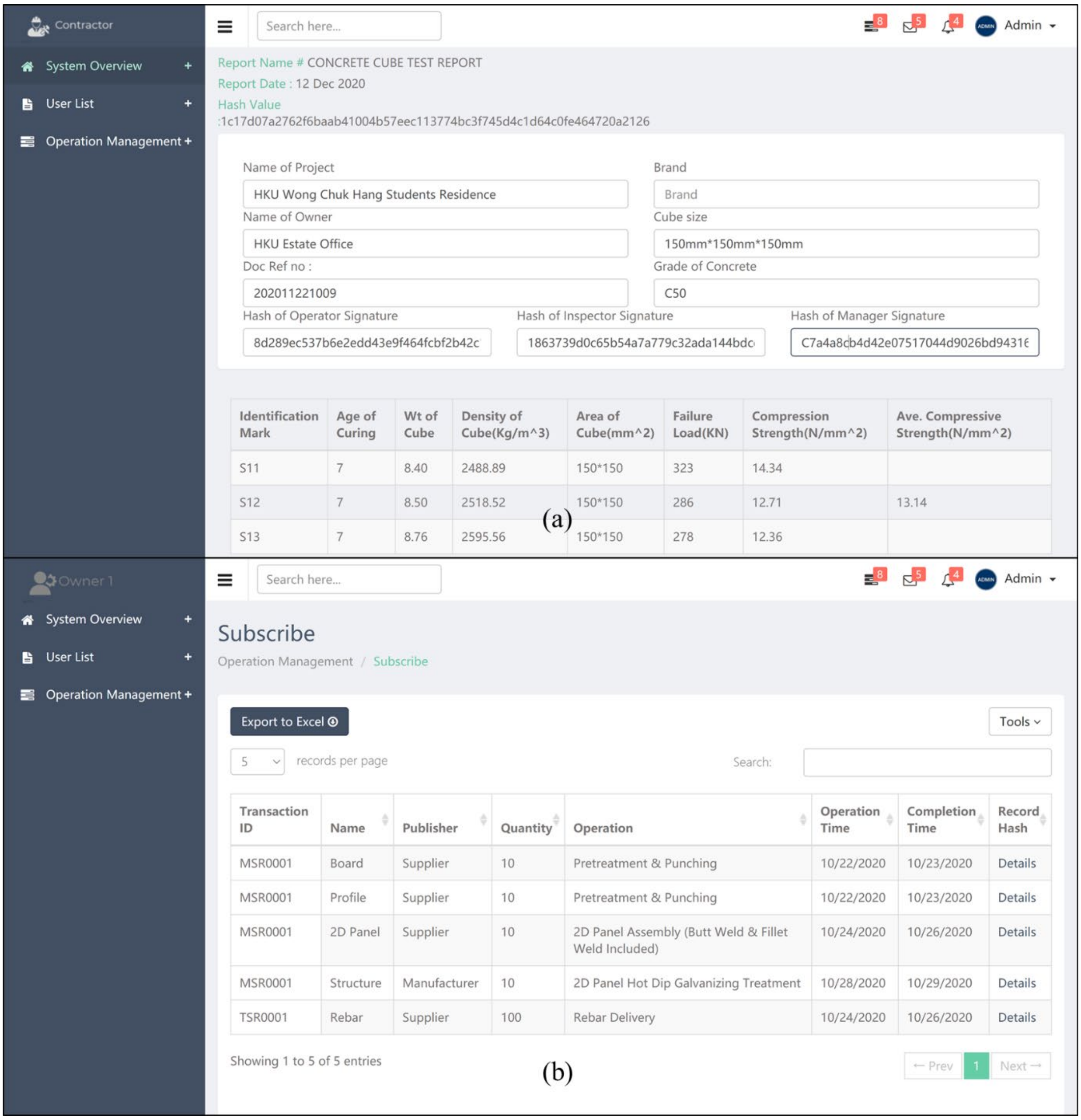

Figure 11. Prototype interfaces for the TABS. (a) Contractor's interface for publishing inspections; (b) Owner's interface for subscribing sidechain's historical operations

5.2 Evaluation and Analysis

This section introduces the performance metrics of storage cost, latency, and privacy to evaluate the TABS prototype in the case study. There are two assumptions: (1) 100 modular products are under production synchronously per day; (2) an average of 5 operations are conducted per modular product per day. The block time can be set as $T_{block} = 0.5$ h/block, that is, a new block is generated per half hour for recording operation information. Thus, each block includes an average of 10 operations through rough calculation.

5.2.1 Storage Cost

According to the OMHP workflow, the number of operations in material supply, production, and inspection is 85 (for a standard room) and 102 (for a toilet). In previous studies, all the detailed information is stored in the blockchain. For example, an quality information form can be around 14.82 KB (Sheng et al., 2020) and may lead to each block size being 148.86 KB. In our study, one transaction's size is around 1 KB, and all the details are saved in the sidechain. The total number of modular products in this project is 1,224 and may only generate 121.92 MB (102 × 1 × 1,224) at the largest case in the main blockchain for the whole project. It is an acceptable size for current blockchain storage capacity. Storage loads can be released from the two-layer adaptive blockchain structure, particularly when some valuable large files, such as video and model data, to track.

5.2.2 Latency

The latency performance in this study was evaluated by measuring the time of publishing transactions. The publishing time refers to the time it takes for a participant to publish a transaction from a sidechain to the main blockchain, and the owner receives the transaction confirmation from the main blockchain network. We tested the time of publishing each transaction from the contractor to the owner. The result of the first 14 transactions is presented in Fig. 12. It can be seen from the result that the latency of the system is at a millisecond level. In the real OMHP inspection process, each transaction may be published a day apart. Some operations for material supply and production are also lengthy processes that can last for a few days. Thus, the latency of the prototype can be negligible.

Figure 12. The latency of the prototype system

5.2.3 Privacy

In the TABS design, detailed operation records are stored in the sidechains of participants, and hash values of these records, together with other operation data, can be published in the main blockchain. The published transaction data and operation data for a modular standard room (MSR) can be found in Table 1 (See Appendix). The detail of the operation record is protected by hash encryption (See Fig. 9 (b)). It ensures the private operation data not revealed to other participants.

6. Discussion

Compared with the previous studies, three aspects of novelty to the proposed TABS model are summarized in the following.

- First, the supervision processes in aspects of transparency, traceability, and immutability have seldom been investigated in the stage of modular housing production, where massive off-site operation records could be generated. Furthermore, the failure of supervision may lead to adverse effects in quality, progress, and cost for the subsequent logistics and on-site assembly stage. Thus, this study defines the supervision scope on three types of spatial-temporal operation records, including material, production, and inspection, based on the OMHP business process analysis with Lean thinking.

- Secondly, previous studies using blockchain in the construction industry make all participants' data stored and traded on one blockchain (Wang et al., 2020; Sheng et al., 2020; Zhang et al., 2020). Compared with the existing blockchain systems in construction, this study proposes a two-layer adaptive blockchain supervision (TABS) model that includes two advantages: (1) Storage cost reduction. TABS allows the detailed operation records stored in the participants' sidechain, which can help reduce the storage cost in the main blockchain, particularly when some valuable large files, such as video and model data, are captured in the operation processes; (2) Privacy-preserving. TABS only trades the hash value of detailed operation records and other operation data (e.g., timestamp, signature, operation name) among the main blockchain. Thus, private operation data can not be revealed to other participants.

- Thirdly, the TABS model is an adaptive structure that can extend and add sidechains from other participants, such as designers, logistics companies, property management companies. Moreover, the publish-subscribe pattern designed in smart contracts can be more proactive than the request-response mode, facilitating the comparison of the transaction hash publish time and operation completion time. It ensures the participant to be diligent in publishing transactions when punishment mechanisms are involved for any delay.

Despite these innovations, our study still has several limitations.

- First, the supervision of each OMHP operation can increase the workloads in each participant and may reduce their interests. Thus, an effective incentive mechanism devised in the TABS may drive them to offer accurate operation data.
- Secondly, the operation data of current OMHP processes are input by humans, and there is no guarantee that malicious data are stored. Thus, reliable blockchain oracles can be the solution, such as the decentralized IoT sensors for operation data uploading.
- Thirdly, the TABS model is a project-based blockchain network, which may need to be adaptive when the related project is completed, and modular products' warranty expired. For example, the cropping mechanism can be an alternative for reducing data redundancy and keeping reliable storage.

7. Conclusion

Blockchain is a disruptive technology that can save the current collaboration from the trust crisis in the construction industry, particularly for fragmented off-site modular housing production (OMHP). Disputes, such as quality defects, delays, cost overrun, always occur without authentic records for checking the responsibility. The current blockchain prototypes in the construction industry have been proved to record tamper-proof operation data. However, the construction companies wish to keep their business data private and may be reluctant to make data accessible to other participants, needless to say, their competitors and the public.

This study presents a two-layer adaptive blockchain-based supervision (TABS) model for OMHP. Firstly, a two-layer adaptive blockchain structure is designed. The first layer is sidechains of OMHP participants, including operation records and matched hash. The second layer is the main blockchain for communication and trading among OMHP participants, including operation records hash, and block information. Thus, the TABS model can avoid tampering with operation records by the main blockchain and drive the participants to promptly publish their operation records without fear of privacy leaks. Secondly, the TABS model realizes OMHP supervision processes, including registration, publish-subscribe, ordering service, and consensus mechanism. To implement the supervision process, smart contracts are created to achieve on-chain and cross-chain interactions. Thirdly, a prototype system is developed to realize the TABS model, and the related performance evaluation is conducted based on a case study. The experiment-based performance evaluation indicates that the TABS model can enhance privacy, reduce storage cost, and have an acceptable latency for modular housing production supervision.

Future research work can enrich and improve the presented TABS model. For example, the incentive and cropping mechanisms designed for the TABS model can improve the data authenticity in the sidechain and reduce the storage redundancy in the main blockchain. Also, integrating BIM and IoT for blockchain can solving the single point of failure in operation data collection. To make TABS more robust and easy to use, TABS will be integrated into a new BaaS (BlockchainBIM as a Service) architecture to work with stakeholders' existing ERP systems; the BaaS architecture will be gauged in more scenarios of modular construction, long-range cross-border logistics, infrastructure projects, and underground work in the real settings. It will also be interesting to expand the TABS model to other manufacturing industries beyond the domain of construction.

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Appendix

Algorithm A.1. Algorithm of publish-subscribe

Algorithm 1 Publish-subscribe

Input: Subscribed hash
Output: Published transaction
Step 1: Subscribe the operation data of production by sending a random hash signal
Owner.get (hash)
Hash → Manufacturer
Step 2: Once the first operation completed, store first operation data (operation, time)
Production operation → Data ()
Completion time → Data ()
Data ()→ Manufacture.sidechain
Step 3: Generate a transaction in the sidechain
Transaction.hash ← SHA256 (Data)
Transaction.prehash ← Hash
Transaction.signature ← Operator.signature ()
Step 4: Publish the transaction to the owner
Transaction → Owner
End

Algorithm A.2. Algorithm of ordering and verification

Algorithm 2 Ordering and Verification

Input: Transactions
Output: Main Blockchain
// **Step 1**: Owner gets and orders transactions by the previous hash in each transaction
Owner.get (transaction)
// **Step 2**: Owner receives production operation data from the manufacturer
Owner.get(Data)
// **Step 3**: Owner creates blocks and checks the data consistency
Owner.createblock (header,transaction)
if *SHA 256 (Data) != transaction.hash*
  Return *False*
// **Step 4**: Owner broadcasts the block to participants
  Block → Contractor
  Block → Manufacturer
  Block → Supplier
// **Step 5**: Each participant verified the block and signed it
  if *Block.manufacturer_signature.error()* ***OR*** *Block.supplier_signature.error()*
    OR *Block.contractor_signature.error()*
  Return *False*
  else
  Owner.signature (Block)
// **Step 6**: Owner update the verified block to the world state
Block → Main Blockchain
End

Table A.1 Example operation records in transaction data

Process	Publisher	Transaction	Operation Details
Material Supply	Supplier	{"Material": Material operation 01, 10/22/2020}	["MSRID":"MSR0001","Name":"Board", "Quantity":"10", "Operation":"Pretreatment & Punching","OperationTime":"10/22/2020","Completio Time":"10/23/2020","Record":"Details"]
		{"Material": Material operation 02, 10/22/2020}	["MSRID":"MSR0001","Name":"Profile", "Quantity":"10", "Operation":"Pretreatment & Punching","OperationTime":"10/22/2020"," CompletionTime":"10/23/2020", "Record":"Details"]
		{"Material": Material operation 03, 10/24/2020}	["MSRID":"MSR0001","Name":"2D Panel", "Quantity":"10", "Operation":"2D Panel Assembly & Delivery (Butt Weld & Fillet Weld Included)","OperationTime": "10/24/2020","CompletionTime":"10/26/2020", "Record":"Details"]
		{"Material": Material operation 04, 10/24/2020}	["MSRID":"MSR0001","Name":"Rebar", "Quantity":"100", "Operation":"Rebar Delivery","OperationTime":"10/24/2020"," CompletionTime":"10/26/2020","Record":"Details"]
		……	
Production	Manufacturer	{"Production": Production operation 01, 10/28/2020}	["MSRID":"MSR0001","Name":"Structure", "Quantity":"10", "Operation":"2D Panel Hot Dip Galvanizing Treatment","OperationTime":"10/28/2020", "CompletionTime":"10/29/2020","Record":"Details"]
		{"Production": Production operation 02, 10/30/2020}	["MSRID":"MSR0001","Name":"Structure", "Quantity":"1", "Operation":"3D Assembly including Welding Work for Bondek, Shear Stud, Bracket, Wall & CeilingSheet","OperationTime":"10/30/2020", "CompletionTime":"11/03/2020","Record":"Details"]
		{"Production": Production operation 03, 11/04/2020}	["MSRID":"MSR0001","Name":"Structure", "Quantity":"1", "Operation":"Touch-up Galvanized Paint (Zinc Rich Primer)","OperationTime": "10/24/2020","CompletionTime":"10/26/2020", "Record":"Grade Details"]
		…...	
Inspection	Contractor	{"Inspection": Inspection record 01, 10/22/2020}	["MSRID":"MSR0001","Name":"Board", "Types":"Hold Point", "Operation":"Material Grade and Size Spot Check","OperationTime":"10/22/2020", "CompletionTime":"10/23/2020","Results":"Qualified","R ecord":"Grade Details"]
		{"Inspection": Inspection operation 06, 10/29/2020}	["MSRID":"MSR0001","Name":"Structure", "Types":"Hold Point", "Operation":"2D Panel Weld Test, Visual Inspection (Butt Weld and Filet Weld) ","OperationTime":"10/29/2020","CompletionTime":"10/3 0/2020","Results":"Qualified","Record":" Test Details"]
		{"Inspection": Inspection operation 07, 11/04/2020}	["MSRID":"MSR0001","Name":"Structure", "Types":"Hold Point", "Operation":"Cladding Sub Frame Alignment Check","OperationTime": "11/04/2020","CompletionTime":"11/05/2020","Results": "Qualified"","Record":"Alignment Details"]