Using blockchain to improve information sharing accuracy in the onsite assembly of modular construction

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Abstract

Onsite assembly is a critical stage for modular construction. Its success or failure depends on accurate information sharing among numerous stakeholders who, unfortunately, often possess unsynchronized information. Owing to its decentralized consensus mechanism, blockchain has the potential to improve information-sharing accuracy on construction sites. However, little research has documented how this can be done. Adopting a design science research (DSR) method, this study aims to explore the use of blockchain technology to improve information-sharing accuracy in the onsite assembly of modular construction (OAMC). Firstly, an OAMC business process analysis is conducted to understand the issues leading to information sharing, in particular its accuracy. Then, a blockchain-based conceptual model is developed. Its components such as membership registration, information sharing-request, ordering service, consensus mechanism, and distributed storage are described. Finally, a prototype system is developed and validated in a mock-up OAMC. The results show that the prototype system can improve the accuracy of information sharing in OAMC by allowing project participants to endorse information about the modules and their assembly through the blockchain's consensus mechanism. This study explores and implements blockchain technology in a specific construction area. It can serve as a valuable reference for future endeavors in harnessing the power of blockchain technology, particularly for mobilizing information endorsement mechanisms for various value-added applications.

Keywords: Blockchain; Accurate information sharing; Information endorsement/consensus mechanism; On-site assembly; Modular construction.

Introduction

Modular construction involves fabricating 3D-volumetric building "modules" under controlled offsite conditions and transporting them to a building site for assembly into a final construction product (Li et al., 2021). It can reduce construction time, save labor, improve worker safety, and help to achieve environmental sustainability goals (Gong et al., 2019). However, successful project delivery involves complex onsite assembly with myriad stakeholders (e.g., owners, contractors, subcontractors, and transporters) who interact frequently based on an array of information (Luo et al., 2020). Thus, onsite assembly in modular construction (OAMC) requires to share accurate information to minimize the issues related to assembly rework, labor, time, and occupational health and safety (Li et al., 2019a).

There are several causes to inaccurate information sharing in OAMC. One is the widespread use of paper or paint labels (Li et al., 2018a). They are too ambiguous to guarantee the accuracy of OAMC information exchanged (e.g., assembly sequence, module type, installation location and orientation) (Demiralp et al., 2012). Another reason is the fragmented nature of construction organizations (Zhai et al., 2019). Project participants from different organizations may not have a unified information sharing platform, leading to asymmetric information sharing (Lee et al., 2021b). Inaccurate information sharing in OAMC could also be attributable to a lack of assurance mechanisms for checking updated information (Li et al., 2018b; Zhou et al., 2021). In current practice, incomplete or inaccurate change and scheduling information transmitted from previous processes (e.g., production, logistics) may be passed to the OAMC phase without endorsement or with serious latency (Wu et al., 2021).

Emerging from the technology sphere, blockchain could bring about a paradigm shift in the information management practices of construction (Li et al., 2019b). A blockchain is a distributed ledger with cryptography and decentralized consensus mechanisms, which can effectively record and endorse transactions between participants in a shared, secure and traceable manner (Xue and Lu, 2020). Blockchain benefits include reinforced transparency, traceability, immutability, privacy, and automation (Perera et al., 2020), promotion of democratic decision-making through decentralization, and reduced costs through removal of intermediaries (Li et al., 2021). In construction, blockchain applications have been introduced for internal administration (Pradeep et al., 2021), self-executing transactions with smart contracts (Hamledari and Fischer, 2021), immutable records of transactions (Zhong et al., 2020), secure payment (Das et al., 2020), and combined applications with Internet of things (IoT) (Elghaish et al., 2021), building information modeling (BIM), and cloud computing (Li and Kassem, 2021). Although blockchain-based solutions (e.g., Wang et al., 2020; Sheng et al., 2020; Zhong et al., 2020; Hijazi et al., 2021; Tao et al., 2021) have been proposed for information management problems (e.g., information sharing, data traceability, and record immutability) in construction, its applicability to the problem of improving information-sharing accuracy for OAMC has received little attention. For researchers, a clear theoretical model is needed to explain how blockchain can improve information sharing, while practitioners desire an operable system.

The aim of this research is twofold: (a) to explore theoretical explanations for how blockchain can improve information-sharing accuracy; and based on that, (b) to provide empirical examples of mobilizing blockchain technology to improve information-sharing accuracy in the context of OAMC. It adopts a design science research (DSR) method involving a literature review, business process analyses (BPA), prototyping, onsite testing, validation, and interviews at construction project sites. The remainder of this paper is organized as follows. Subsequent to this introduction is a literature review of blockchain for assembly services and its applications in information sharing. The following section elaborates on the research methodology. Then the results of BPA are described, providing the basis for developing the theoretical model. After that, the components of this model are elaborated, based on which a prototype system is developed, validated, and reported. Research findings and the strengths and limitations of the study are discussed, and then conclusions are drawn in the last section.

Literature Review

Blockchain technology for assembly services

Blockchain technology has been applied to assembly services in various industries. To ensure a tamper-proof history of product assembly, for example, Mondragon et al. (2018) adopted blockchain to record information related to composite materials. In the automotive industry, Dorri et al. (2017) proposed a blockchain-based architecture to immutably record vehicle assembly information. Similarly, Ravishankar et al. (2020) used blockchain to record information related to clutch lever assembly. Other studies have explored blockchain traceability and transparency in assembly services. For example, Kuhn et al. (2021) designed a blockchain architecture to enhance the traceability of automotive assembly materials. Huang et al. (2020) used blockchain to enhance information-sharing efficiency among participants during turbine assembly. However, little research has attempted to address blockchain potential for information endorsement in assembly services where efficient collaboration requires accurate shared information.

In construction, numerous studies have focused on the use of blockchain in supply chain tracking. For example, Sheng et al. (2020) and Zhang et al. (2020) used blockchain to track prefabricated components from production to onsite assembly. Wang et al. (2020) explored blockchain for sharing information on component location for onsite assembly, while Zhong et al. (2020) and Wu et al. (2021) developed blockchain prototype systems to record prefabricated component quality information. Although blockchain-based solutions have been proposed for data traceability, information sharing, and record immutability in construction, its applicability to improving OAMC information-sharing accuracy has not yet been systematically examined.

Blockchain technology for information-sharing endorsement

Blockchain protocol incorporates an endorsement (consensus) mechanism to verify the correctness of block contents (Xue and Lu, 2021). Only when blockchain network participants have verified the transaction information can it be included in the blockchain as a new block. Four common consensus algorithms are: proof of work (PoW), proof of stake (PoS), practical byzantine fault tolerance (PBFT), and crash fault tolerance (CFT) (Lu et al., 2021a). PoW is typical in finance (Chen et al., 2017), philanthropy (Sirisha et al., 2019), and democracy and governance (Diallo et al., 2018) because it is an open consensus algorithm that can ensure the transparency of transactions. However, it needs high computing power (Lu et al., 2021a). A relatively energy-saving mechanism, PoS assumes that participants with a greater stake (e.g., coins) display less opportunistic behavior, so they have more opportunities to endorse blocks. PoS is an open consensus algorithm with relatively low privacy. It has been adopted by Pop et al. (2018), for example, to verify information in the energy industry. PBFT is a permissioned network's consensus protocol, a low-energy mechanism that requires three rounds of voting (Perera et al., 2020). It was selected by Wang et al. (2019), for instance, to verify education certificates. However, it is not a cost-effective choice for relatively small blockchain networks (Hyperledger Fabric, 2020). CFT is another low-energy mechanism. It does not, for example, require cryptocurrency participants to conduct expensive mining to verify transactions (Perera et al. 2020).

In construction, blockchain conceptual models and proof-of-concept works related to information endorsement have recently been investigated in procurement (Yang et al., 2020), production (Li et al., 2021), quality (Sheng et al., 2020; Zhang et al., 2020; Zhong et al., 2020), and progress (Wang et al., 2020; Tezel et al., 2021). However, the effectiveness and efficiency of the consensus mechanism in ensuring accurate information-sharing remains to be studied. For example, while Pradeep et al. (2021) proposed a blockchain framework to verify design inputs, it was not evaluated in real-life cases. Das et al. (2020), Hamledari and Fischer (2021) and Hasan and Salah (2018) focused on blockchain-based payment verification, but on the security and transparency of payments rather than the effectiveness and efficiency of endorsement mechanisms. Dounas and Lombardi (2018), meanwhile, integrated computer-aided design (CAD) and blockchain to endorse CAD modifications, but their work only allows verifying operation-based transactions from CAD applications. Most frequently, blockchain is used in construction to verify changes in digital models, especially BIM (Hunhevicz and Hall, 2020). Lee et al. (2021a) developed and tested an integrated digital twin and blockchain framework for sharing, verifying, and tracking project data, using a case study to show that the consensus mechanism could prevent hacked information from being shared. Nevertheless, whether such a mechanism could improve information-sharing accuracy in construction was largely unexplored.

Table 1 summarizes the relevant research on the use of blockchain technology for endorsement in information sharing. The research gaps are summarized by analyzing the target problem and the adopted platform, consensus mechanism, and testing method, revealing lack of a model to guide the establishment of an endorsement mechanism for information sharing in OAMC. In addition, effectiveness of the consensus mechanism in improving accuracy of information sharing in OAMC has not been empirically evaluated.

Table 1. Included studies related to information endorsement using blockchain technology

ID	Reference	Target problem	Blockchain platform	Consensus mechanism	Testing method
Non-construction industry					
1	Chen et al. (2017)	Cryptocurrency transaction endorsement	Bitcoin	PoW	Prototype development
2	Diallo et al. (2018)	Bidding information endorsement	A custom blockchain	PoW	Prototype development
3	Dounas and Lombardi (2018)	Design information endorsement	Ethereum	PoW or PoS	Prototype development
4	Pop et al. (2018)	Energy information endorsement	Ethereum	PoS	Simulation
5	Sirisha et al. (2019)	Donation information endorsement	Ethereum	PoW	Prototype development
6	Wang et al. (2019)	Education certificate endorsement	Hyperledger Fabric	PBFT	Case study
Construction industry					
7	Hasan and Salah (2018)	Digital assets information endorsement	Ethereum	PoS	Prototype development and security analysis
8	Das et al. (2020)	Progress payment information endorsement	Ethereum	PoS	Comparative analysis
9	Sheng et al. (2020)	Quality information endorsement	Hyperledger Fabric	Kafka consensus	Prototype development and case study
10	Wang et al. (2020)	Production and transportation information endorsement	Hyperledger Fabric	PBFT	Case study
11	Xue and Lu (2020)	BIM modification endorsement	A custom blockchain	A custom consensus	Simulation
12	Yang et al. (2020)	Design and Procurement information endorsement	Hyperledger Fabric Ethereum	PBFT PoS	Case study
13	Zhang et al. (2020)	Quality information endorsement	Hyperledger Fabric	PBFT	Interview
14	Zhong et al. (2020)	Quality information endorsement	Hyperledger Fabric	PBFT	Prototype development
15	Hamledari and Fischer (2021)	Progress payment information endorsement	Ethereum	PoW	Case study

16	Li et al. (2021)	Module production information endorsement	Hyperledger Fabric	PBFT	Prototype development
17	Lu et al. (2021a)	Project application information endorsement	Hyperledger Fabric	CFT	Prototype development
18	Lee et al. (2021a)	Project-related information sharing and endorsement	Ethereum	PoW	Case study
19	Wu et al. (2021)	Quality information endorsement	Hyperledger Fabric	PBFT	Prototype development
20	Pradip et al. (2021)	Design information endorsement	Ethereum	PoW	Prototype development
21	Tezel et al. (2021)	Progress payment information endorsement	Ethereum	PoW	Focus group studies

Research Methodology

This study adopts design science research (DSR) method, an analytical and creative approach that involves creating meaningful artifacts to solve identified problems (Pradeep et al., 2021). The four steps involved are shown in Fig. 1.

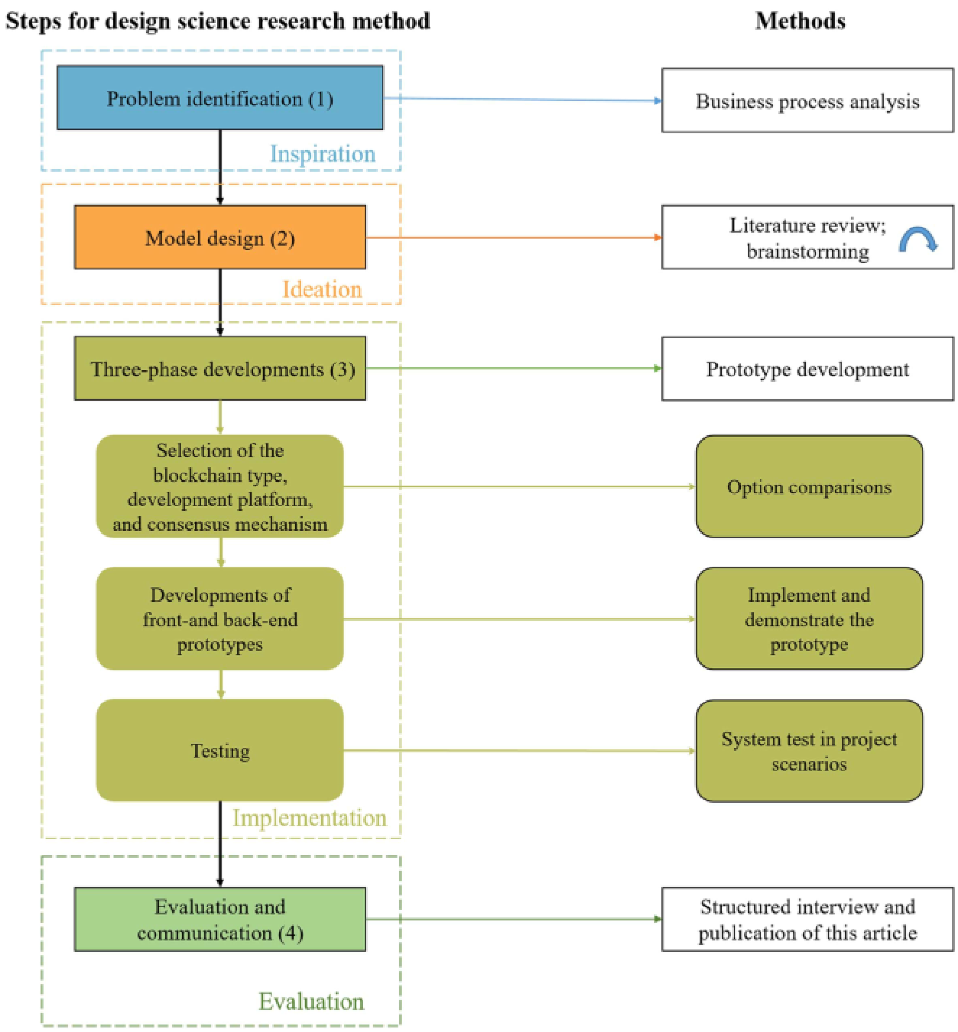


Fig. 1. Methodological steps

The first step was to understand the issues leading to sharing of inaccurate information. The research team conducted BPA of multiple modular construction projects, onsite assembly processes in particular, to identify problems related to information-sharing endorsement faced by key stakeholders (e.g., owners, transporters, contractors, and inspectors). The research team also introduced basic blockchain knowledge (e.g., encryption algorithm, consensus mechanism, distributed ledger) to project representatives and discussed how it might improve information-sharing endorsement in OAMC. A student residence modular construction project was selected for the study with the scope of the OAMC phases defined as: (1) the owner signs an agreement to confirm the start time of the site survey; (2) prefinished modules and their related detailed information are delivered (i.e., the inputs); (3) external systems are completed, and relevant inspections are passed; (4) structural towers are completed (the output).

The second step involved developing a blockchain-based model. Four research meetings were carried out in January 2021. At the first meeting, the research team identified the stakeholders involved and confirmed the OAMC information that needed to be endorsed. At the second, team members brainstormed the model structures by analyzing and synthesizing the literature and knowledge obtained in the first step. The advantages and disadvantages of solutions were discussed in the third meeting, based on which the most promising was selected. The process was non-linear because, as some solutions were feasible but not the most promising, several comparison iterations were needed to select a promising solution. Finally, for this solution, the model was proposed and graphed in the fourth meeting.

The third step included the three-phase development and testing of the prototype system. Firstly, blockchain type was determined by considering the strengths and weaknesses of public, private, and consortium blockchain (Perera et al., 2020). As Zhong et al. (2020) pointed out, consortium blockchain can provide complete functions such as authentication, authorization, and audit of participating members. This blockchain type was chosen as different parties may have different requirements for information and privacy control in OAMC. Hyperledger Fabric platform was adopted to develop the consortium blockchain since it provides developers with diverse security-enhanced alternatives, guidelines, resources and tools, and is suitable for complex information proof requirements in construction (Li et al., 2021). Next, a consensus algorithm was selected. Unlike other open consensuses such as PoW and PoS, CFT avoids cryptocurrency, reducing vital risks/attack vectors and requiring lower computational energy consumption from cryptographic mining processes (Perera et al., 2020). CFT is also relatively fast compared with PBFT and, compared with PoW, avoids crashes and network partitions (Hyperledger Fabric, 2020). It should be noted that these consensus mechanisms are not mutually exclusive, and the proposed model can have pluggable consensuses supporting different applications or application requirements.

In the next phase, front- and back-end prototypes were developed. The development environment was Linux version 5.4.0-58-generic-lpae (5.4.0-58.64~18.04.1) (Ubuntu 18.04.1 LTS). The back-end prototype was achieved through SpringBoot (version 2.4) because it is a Java-based back-end framework for the fast and easy development of database management systems (MYSQL) and Web servers. AdminLTE was selected for the fast development of user interfaces as it is a bootstrap-based front-end framework that provides responsive, reusable, and commonly used components. Hyperledger Fabric Cello was used to provide members with access to browse the information on the blockchain. Also, JavaScript as an object-oriented and high-level language was adopted for smart contract writing. In Hyperledger Fabric, smart contracts are packaged as chaincode, which can automate the execution processes. Finally, two training workshops were provided for participants to test the prototype system in the mock-up onsite assembly phase of the surveyed project.

In the fourth step, structured interviews were conducted to reveal reactions and opinions of the parties involved in the proposed prototype system test. Universally used in social sciences, the questions and often the answer categories are fully developed and placed in an interview schedule before the interview begins (Lewis-Beck et al., 2004). The four procedures suggested by Lewis-Beck et al. (2004) were implemented in the interviews. Firstly, the questions were asked as they were worded and in the pre-defined order according to the interview schedule. Secondly, if an interviewee failed to answer the question completely, follow-up questions were asked. Thirdly, the answers were recorded without discretion by the interviewer. Fourthly, the interviewer minimized personal judgment and feedback in order to obtain accurate answers. The interviewees met all three selection criteria. First, they participated in the blockchain introduction session at the BPA stage to ensure that they have basic blockchain knowledge. Second, they attended two system training workshops during the development and testing stage. Third, they were involved in the three testing scenarios. As a result, four participants from the owner organization, two from the contractor, one from the transporter, and one from the inspection organization were asked four pre-worded questions in the same order, as shown in Table 2. The interviewees' answers were recorded and transcribed for further analysis.

Table 2. Information of interviewees and interview questions

ID	Organization	Position	Working Experience
OW1	Owner	Technical Manager	6
OW2	Owner	Project Manager	4
OW3	Owner	Site Engineer	2
OW4	Owner	Site Engineer	2
MC1	Main Contractor	Project Controls Manager	4
MC2	Main Contractor	Site Engineer	3

TR1	Transporter	Logistics Operator	4
INS1	Inspector	Inspector Manager	3
Interview questions			
Question 1: What are the advantages of the prototype system?			
Question 2: What are the disadvantages of the prototype system?			
Question 3: Would you use the prototype system? Why/Why not?			
Question 4: Do you have other suggestions to improve the prototype system?			

Data Analyses, Results, and Findings

Business Process Analysis of Onsite Assembly of Modular Construction

The existing OAMC business process can generally be divided into the 10 main stages shown in Fig. 2 (Li et al., 2018a; Li et al., 2019c). Stages 2 and 3 can be carried out concurrently, as can Stages 4 to 5. Onsite assembly is most relevant to Stage 8.

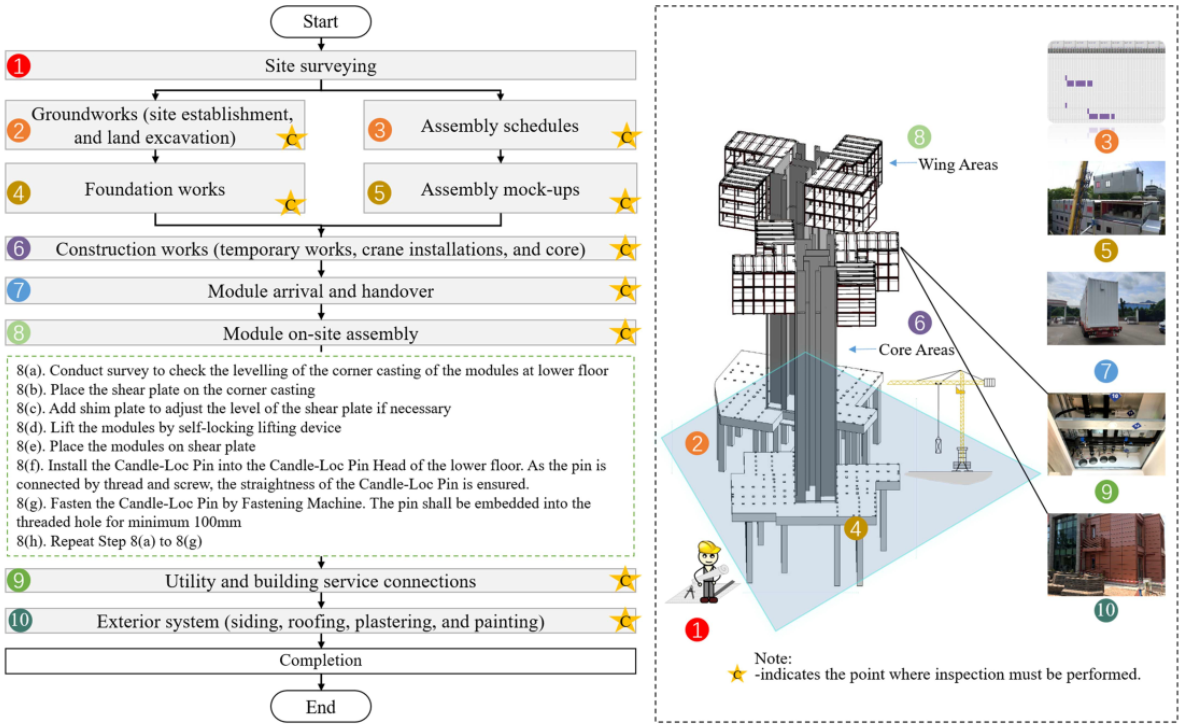


Fig. 2. Onsite assembly processes of modular construction

As shown in Fig. 2, in Stage 1, the site surveyor inspects the area for the proposed construction project and collects information for the follow-up works. In Stage 2, the contractor can establish the site and excavate the land. Procedures for site establishment include protecting existing structures, boundary removal, clean-up of materials, construction of temporary accommodation, and connection of services (Li et al., 2018a). In Stage 3, construction stakeholders can formulate the assembly schedule according to the master plan.

Assembly mock-ups can be carried out in Stage 4 while conducting foundation works in Stage 5.

The construction works begin in Stage 6 and include temporary work (e.g., placing safety signs), crane installation (e.g., erecting a tower crane, material and passenger hoists), and core structure construction (e.g., applying the cast-in-situ method) (Zhai et al., 2019). In Stage 7, according to the plan, the logistics company transports the prefabricated modules to the site and, if the site is too congested to accommodate these massive modules, will temporarily store them in intermediate warehouses nearby. Upon arrival at the construction site, the site engineer will confirm the type, arrival time, quantity, and quality of the modules delivered and sign the delivery docket. In Stage 8, modules are assembled onsite after verification of assembly sequence, module type, installation position, and orientation. Module assembly follows Stages 8(a) to (g) (see Fig. 2). In Stage 9, utilities and building services-related facilities are installed and connected, including plumbing, drainage, gas, electricity, lifts, and fire services. In Stage 10, the exterior system is completed, such as the finishing works (e.g., plastering and painting) for flats, common areas, and external walls.

There are several problems in the OAMC business process. Firstly, accuracy of information sharing is not guaranteed due to ambiguity of paper-based documentation. Secondly, a unified OAMC information exchange platform is lacking, resulting in information asymmetry. Thirdly, the current practice lacks an endorsement mechanism to ensure the accuracy of the updated information (e.g., assembly sequence, module type, installation location, and orientation), leading to module misplacement and additional labor and time costs.

A Blockchain-based Model for Improving Information-sharing Accuracy in Onsite Assembly of Construction Modules

The conceptual model

Based on the literature review and BPA, a conceptual model is proposed to explain how blockchain can be used to improve the accuracy of information shared, as shown in Fig. 3. The blockchain system functions by (1) allowing the owner, contractor, transporter, and inspector to endorse OAMC information; and (2) improving information-sharing accuracy by requiring participants to sign the endorsed information digitally.

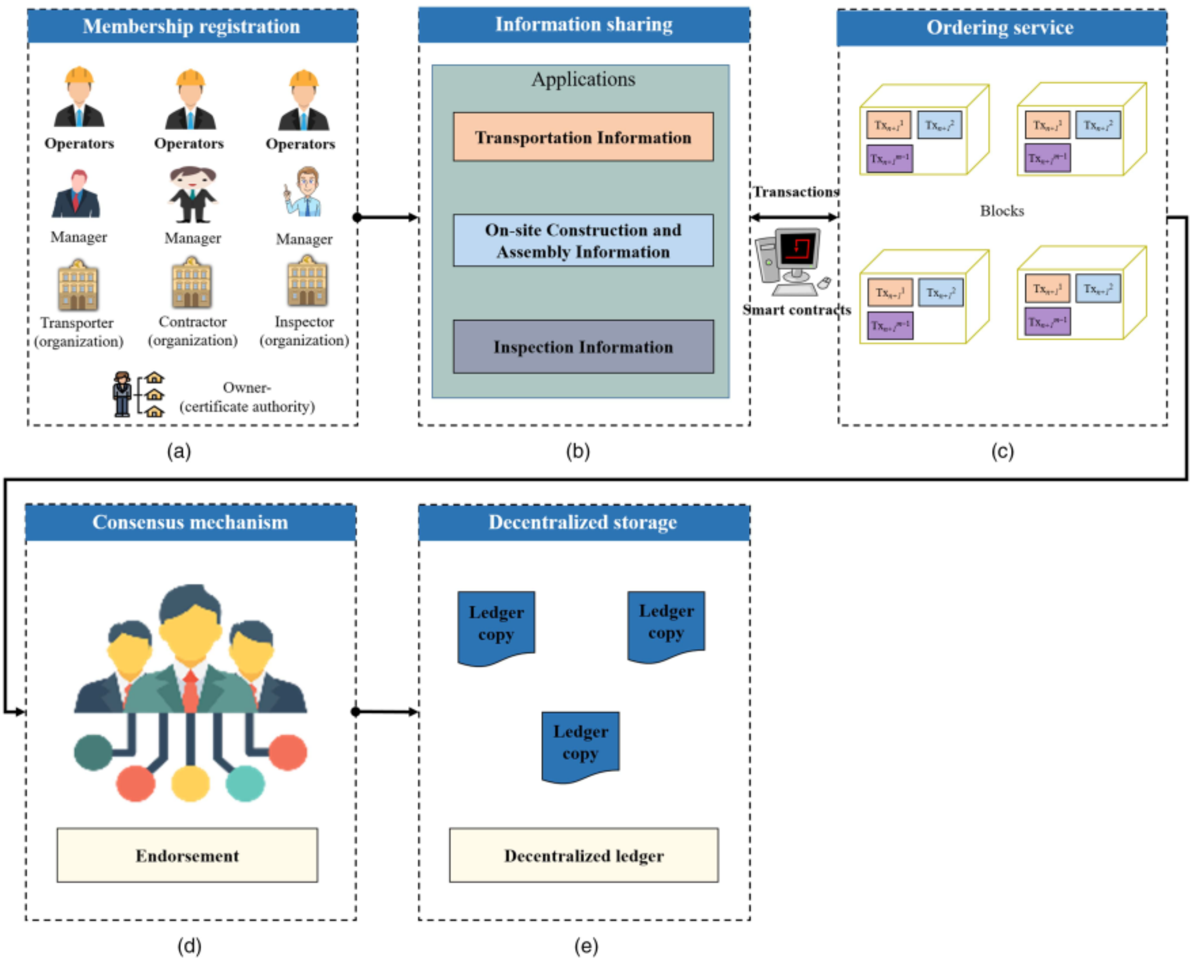


Fig. 3. Blockchain-based model for improving information-sharing accuracy in the onsite assembly of modular construction. (a) membership registration; (b) information sharing; (c) ordering service; (d) consenus mechanism; and (e) decentralized storage.

The proposed conceptual model consists of five components (Fig. 3(a)–(e)). Specifically, OAMC participants should first register as members of a blockchain-based network (Fig. 3(a)) and share relevant information among participants through the corresponding applications (user interfaces) (Fig. 3(b)). Defined OAMC information includes transportation, onsite construction and assembly, and inspection information. Every time information is shared, the smart contract converts it into a transaction and sends it to the ordering service through which transactions are packed as blocks (Fig. 3(c)). In the real-life onsite assembly, it is difficult to verify OAMC information among all stakeholders and also to verify information changes promptly. To enhance the OAMC information endorsement process, the proposed model uses a consensus algorithm. The model also requires participants to digitally sign each transaction when verifying OAMC information, thereby ensuring the completeness and accuracy of the information (Fig. 3(d)). Each participant configures a copy of the ledger to record endorsed transaction information, and the smart contract can invoke the stored transaction information from the ledgers when the participant requests (Fig. 3(e)).

An operable blockchain-based model

The components of the proposed model, such as membership registration, information sharing-request, ordering service, consensus mechanism, and distributed storage, are described as follows. Before joining the network, participants must verify their identity by sending a membership registration request to the owner. Those qualified are allocated Certificate Authorities (CAs) by the owner. Members can provide membership to sub-members through their assigned CAs. The proposed model consists of a network with four registered organizations (members): transporter (T1), contractor (C2), inspector (I3), and project owner (P0), as shown in Fig. 4. All four organizations have a corresponding CA (1–4) authorized by the P0 (the P0 authorises its own CA). The network has a configuration, CC1, which lists the organizations' definitions. The transporter, contractor and inspector can add managers as peers (sub-members), named TP1, CP2, and IP3, respectively, to the channel. Also, peers can add their corresponding operators to share operation information.

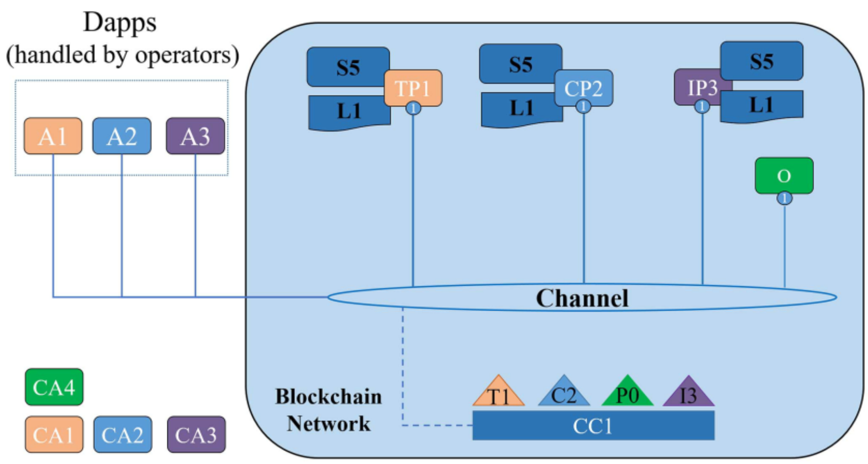


Fig. 4. Registered members of the blockchain-based network

An information sharing-request mechanism is employed to drive transaction flow. Transportation, onsite construction and assembly, and inspection information are shared with the project owner by peers' operators through applications A1 (transportation information sharing user interfaces), A2 (onsite construction and assembly user interfaces), and A3 (inspection information sharing user interfaces), respectively. Transportation information contains data about the module name and ID, process name and ID, delivery date, quantity and quality status of modules (before loading, after loading, and on arrival), vehicle and driver information, location, speed and time records, pick-up time, and signature of the person in charge. Onsite construction and assembly information includes data about construction and assembly operations, while inspection information includes detailed inspection and quality test results for all control points. For example, before assembling modules onsite, the contractor's operators can share module information (e.g., assembly sequence, module type, installation location, and orientation) with the managers (peers) of the inspector and owner in the network to verify its correctness. In turn, the owner can request the module information before assembly, and the corresponding contractor's operator can then exchange module information with the owner in the blockchain. Adopting the same mechanism, the owner can build information sharing-request interactions with the transporter and inspector.

The model uses an ordering service to build orderly blockchain. In this model, the owner serves as an ordering node that bundles transactions into new blocks. The ordering node cannot commit unverified blocks to the blockchain, and only passes ordered and bundled blocks to peer nodes for endorsement. The peers verify block orders by examining the current and previous blocks' hash values.

Peers (organization managers) in the network can verify the completeness and accuracy of transactions in the blocks they receive through the designed consensus mechanism. If the transactions are valid, managers can digitally sign them. The model adopts a CFT consensus algorithm to help managers crosscheck onsite assembly transactions and reach an agreement. Finally, each manager keeps a copy of the ledger (L1) of the channel where the information (transactions) is stored. In the proposed model, L1 is assigned to the managers of the transporter, inspector and contractor (TP1, CP2, and IP3, respectively), and each ledger comprises two different but related parts: a world state and a blockchain, as shown in Fig. 5. The ledger world state contains two states, namely key and value. The key provides operation information categories such as "Transportation", "Onsite construction", "Onsite assembly", and "Inspection". The value offers the information content, such as module ID. The second part, blockchain, is a historical record of how objects arrived at their current states. In the blockchain, each block has a block header and a set of transactions. The block header consists of an index (the serial number of the block in the chain), a timestamp, a signature validator, and the hash values of the current and the previous blocks. The data frame includes a timestamp, a signature, the hash values of the present and the previous transactions, and a key–value pair for each transaction. Users can always connect with other peers keeping the same ledger to restore or update the local ledger copy.

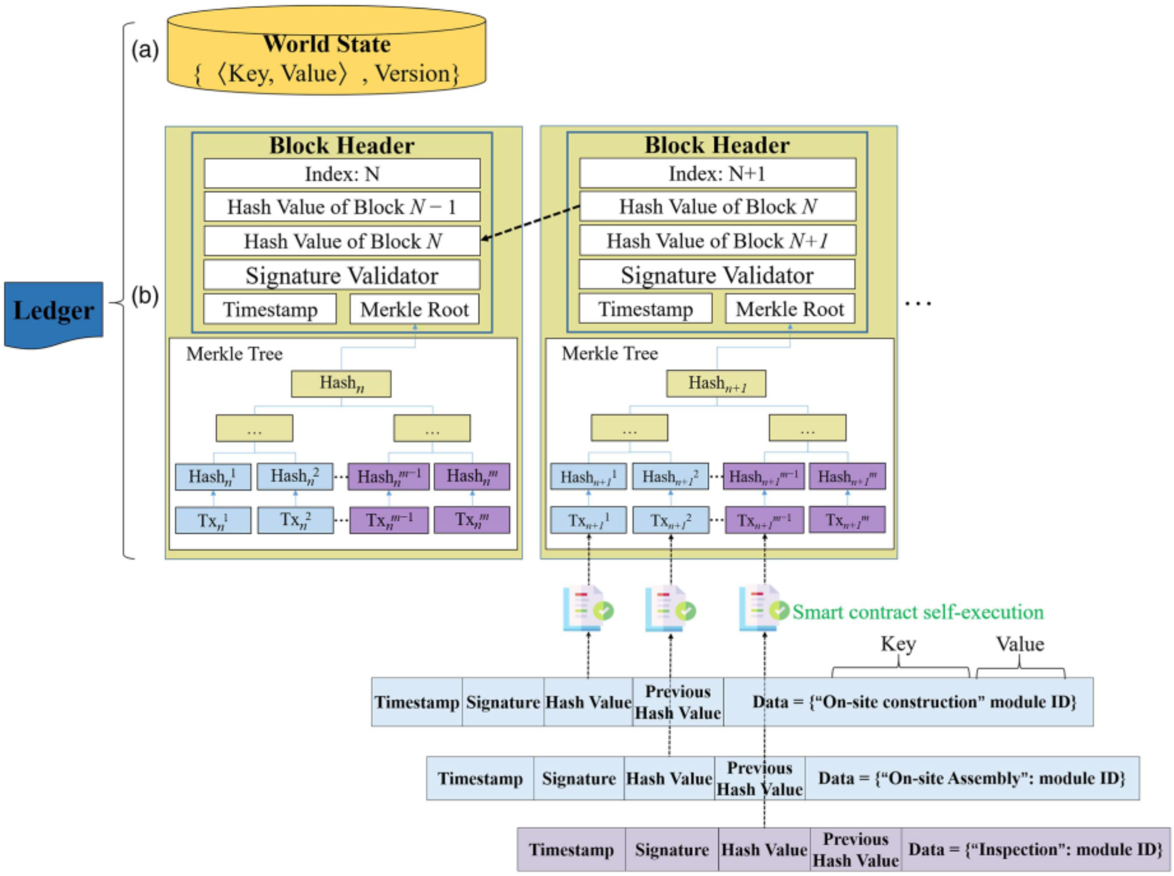


Fig. 5. Ledger: (a) world state; (b) blockchain (Adapted from Li et al. (2021))

In summary, the proposed model has five main information endorsement processes: membership registration, information sharing-request, ordering service, consensus, and distributed storage. Together, they can ensure the accuracy of OAMC information. By requesting the status of any OAMC process, the project owner can achieve better information endorsement and make more effective decisions.

Smart contract configurations

The business logic that defines how peers interact with the ledgers is contained in smart contracts. In the proposed model, chaincode (S5) is installed on TP1, CP2, and IP3. S5 contains two smart contracts, one used for the information sharing-request mechanism, and the other used for block ordering and endorsement. Table 3(a) shows the smart contract algorithm used for the information sharing-request interaction between the owner and the contractor's operator. The owner can request the module information during the onsite assembly process in the blockchain using a hash value as a start signal. The smart contract will ask the contractor's operator to upload the requested transaction information through user interfaces and exchange transaction information with the owner through the blockchain.

It can also help realize the information sharing-request interactions between the owner and the transporter's and the inspector's operators.

Table 3. Smart contract algorithms: (a) information sharing-request; (b) ordering and endorsement

(a) Algorithm Information Sharing-Request

Input: Requested hash value
Output: Published transactions
Step A1: Require the operation data of on-site assembly by sending a hash value signal
Project owner.get (hash)
Hash → Contractor operator
Step A2: After the 1st operation finished, transfer the operation to data (operation, completion time)
Assembly operation →Data ()
Completion time →Data ()
Step A3: Prdocuce a transaction in the blockchain
Transaction.hash ←SHA256 (Data)
Transaction.prehash ←Hash
Transaction.signature ←Operator.signature ()
Step A4: Publish transaction to the project owner
Transaction →Project owner
End

(b) Algorithm Block Ordering and Endorsement

Input: Transactions
Output: Blockchain
// Step B1: Owner recevies and orders transactions
Project owner.get (transaction)
// Step B2: Project owner receives assembly operation data from the contractor operator
Project owner.get (Data)
// Step B3: Project owner packs blocks and endorses the data correctness
Project owner.packblock (header, transaction)
If SHA 256 (Data) != transaction.hash
Return False
// Step B4: Project owner delivers the block to peers
Block → Transporter manager
Block → Contractor manager
Block → Inspector manager
// Step B5: Each peer endorsed the block with digital signature
If Block.transporter manager_signature.error() OR Block.contractor manager_signature. error() OR Block.inspector manager_signature.error()
Return False
else
Project owner.signature (Block)
// Step B6: Project owner updates the endorsed block to the ledger
Block → Blockchain
End

Table 3(b) demonstrates the smart contract algorithm for block ordering and endorsement. This example shows that smart contracts are configured to self-collect transactions published by the contractor's operator and then deliver them to the ordering node (the owner) for bundling into blocks. Next, smart contracts can deliver the blocks to peers for verification. After the blocks are endorsed and signed, smart contracts can commit these blocks to the ledgers.

Development and Testing

Prototype system development

Based on the surveyed modular construction project, a prototype system was developed to implement OAMC information endorsement. In the prototype system, there are four organizations: the owner (acting as the ordering node in the ordering service), the transporter, the contractor, and the inspector. Their configuration information is shown in Fig. 6(a). The cryptogen in Hyperledger Fabric was used to facilitate sub-member registration (e.g., peers and operators) through certificates in order to control access (Fig. 6(b)).

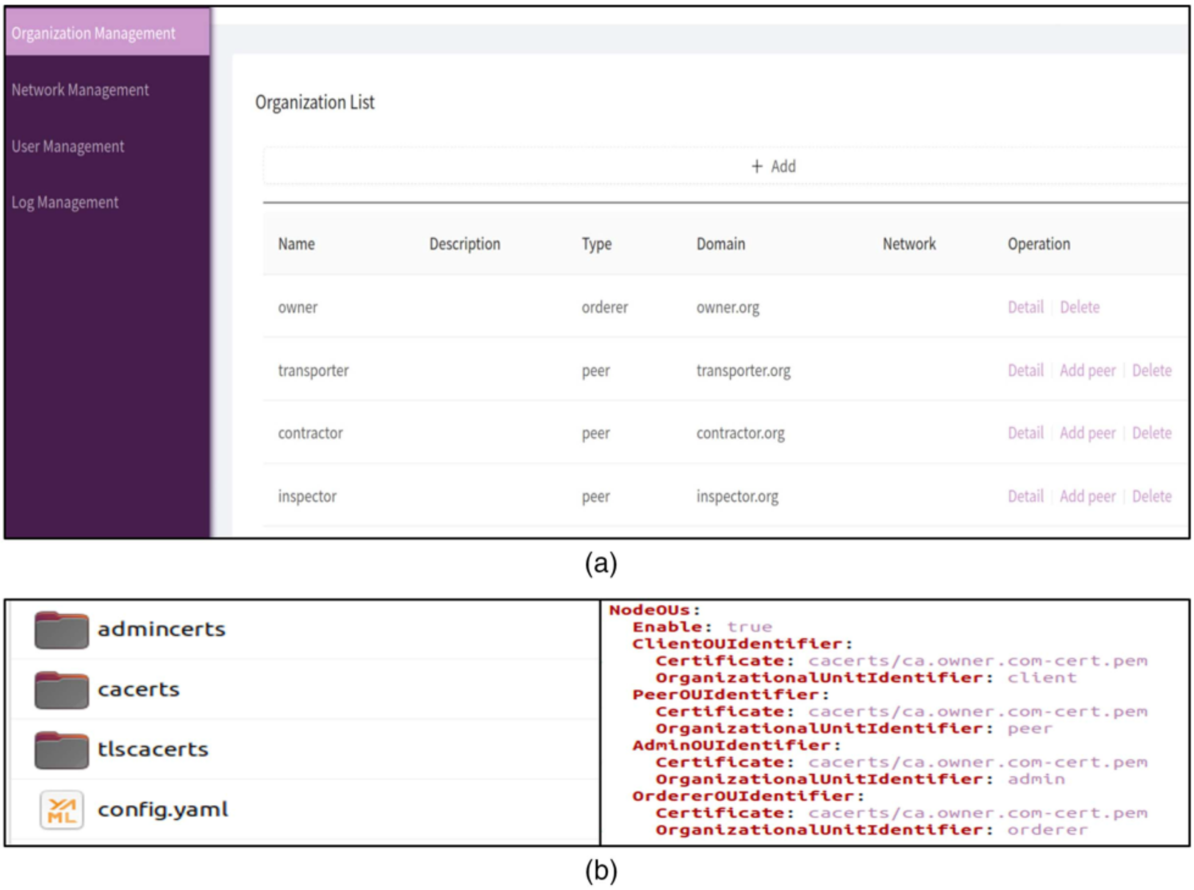
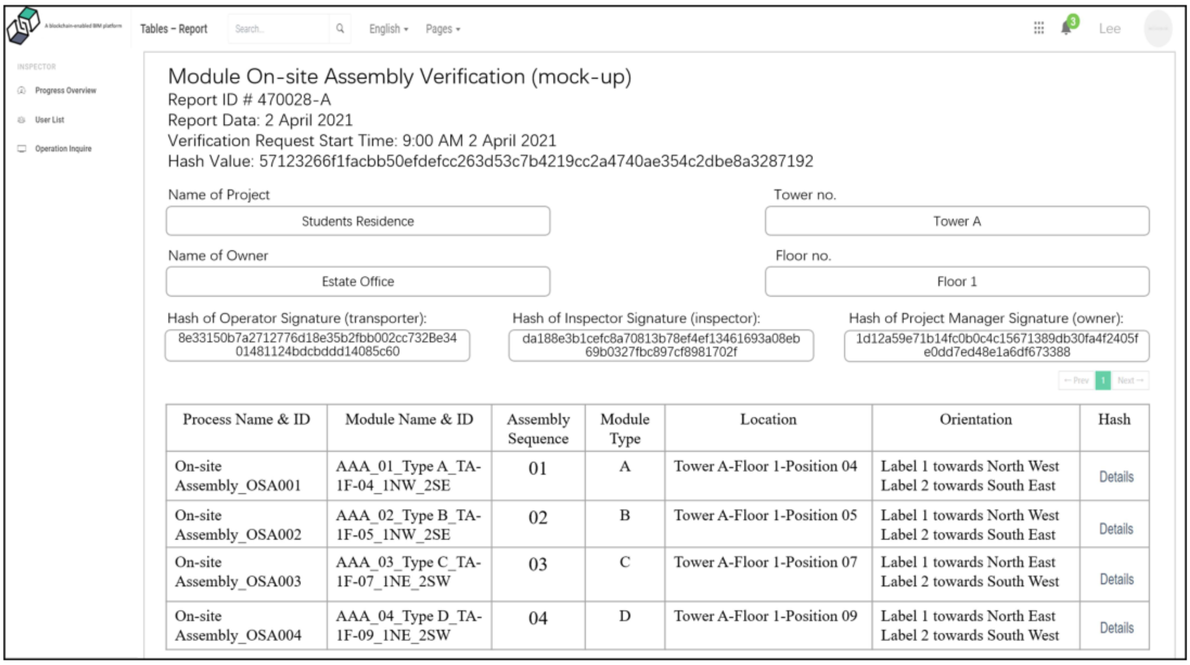


Fig. 6. System configurations: (a) organization registrations; (b) certificates

Through the developed applications (user interfaces) of the prototype, participants such as the contractor’s operators can request other organizations’ managers (peers) to endorse OAMC information. For example, before starting module installation, the operator of the contractor can ask the managers of the owner and inspector to verify the assembly sequence, module type, installation location, and module orientation, as shown in Fig. 7(a). The operators of the transporter and inspector have the same interfaces for submitting information endorsement requests. The endorsement request is converted into a JavaScript Object Notation (JSON) file using the JSON form plug-in. The file is hashed, and the smart contract sends the file to the ordering service. By setting the owner as an orderer in the network, the ordering service is initialized. Next, the CFT consensus mechanism is implemented based on the etcd library in Hyperledger Fabric. The correctness of the information can be established by reaching a consensus among members, and then the verified file is committed to the managers' ledger copies as the latest blocks. For example, the owner can verify the module information through the manager interface before the installation starts, as shown in Fig. 7(b).



(a)

(b)

Fig. 7. User interfaces: (a) contractor's interface for submitting endorsement request; (b) project owner's interface for requesting past transactions

System testing and evaluating

Testing was undertaken by the owner, the transporter, the contractor, and the inspector to demonstrate that the developed model operates as intended. In the test, eight modules (four different types) were delivered to the site in two batches (see Fig. 8(a)). Then, according to the module ID (see Fig. 8(b)), eight modules were installed in the predetermined locations (see Fig. 8(c)) of the construction site to complete the mock-up assembly task of the investigated student residence project.

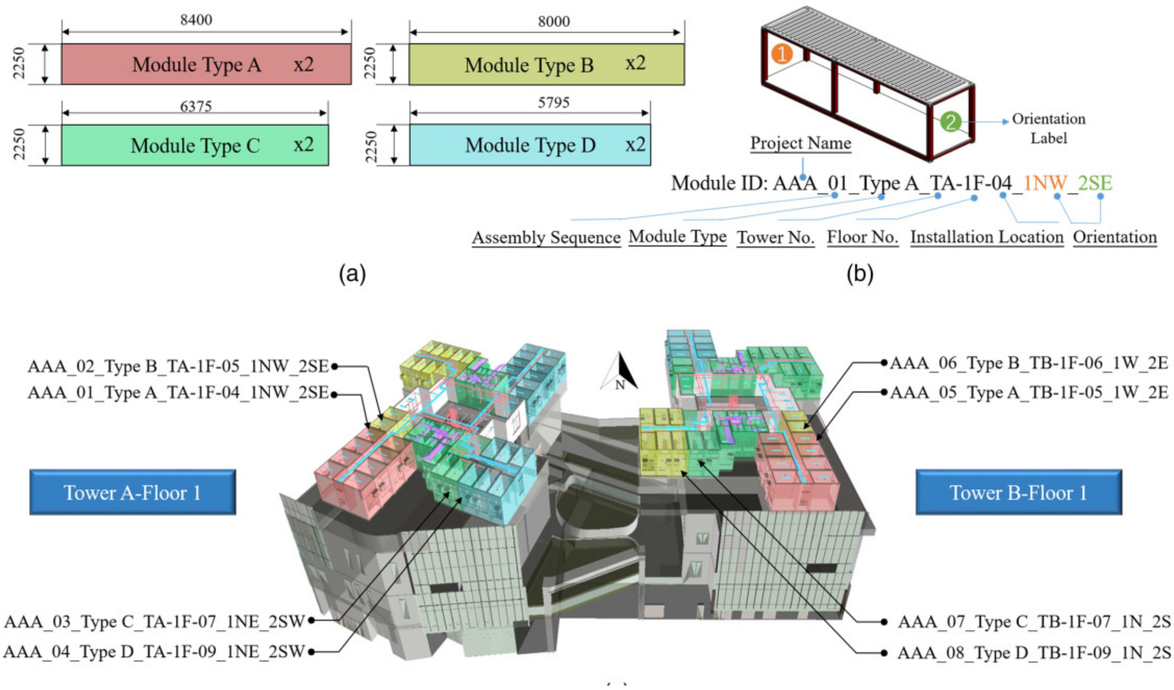


Fig. 8. Mock-up onsite assembly of the surveyed project: (a) module type; (b) module ID; (c) mock-up plan

Test scenarios

Three test scenarios were used to test the performance of OAMC information endorsement processes, as shown in Fig. 9. In the first scenario, the transporter plans to deliver modules from the factory to the construction site (see Fig. 9(a)). The transporter's operator sends out the request through the user interface to the managers (peers) of contractor, inspector, and owner to verify the quantity, quality, and type of the delivered modules. Each endorsement request is recorded as a new transaction, hashed, and uploaded to the blockchain. Once the contractor's and inspector's managers receive the new transactions, they verify the hash values of the transactions. If their digital signatures match the signature of the hash value, these managers can decrypt the transactions and verify the transaction information according to the delivered modules. Then, the owner packs the transactions into a new block and adds the block to the blockchain. Each block generation is endorsed through the CFT consensus.

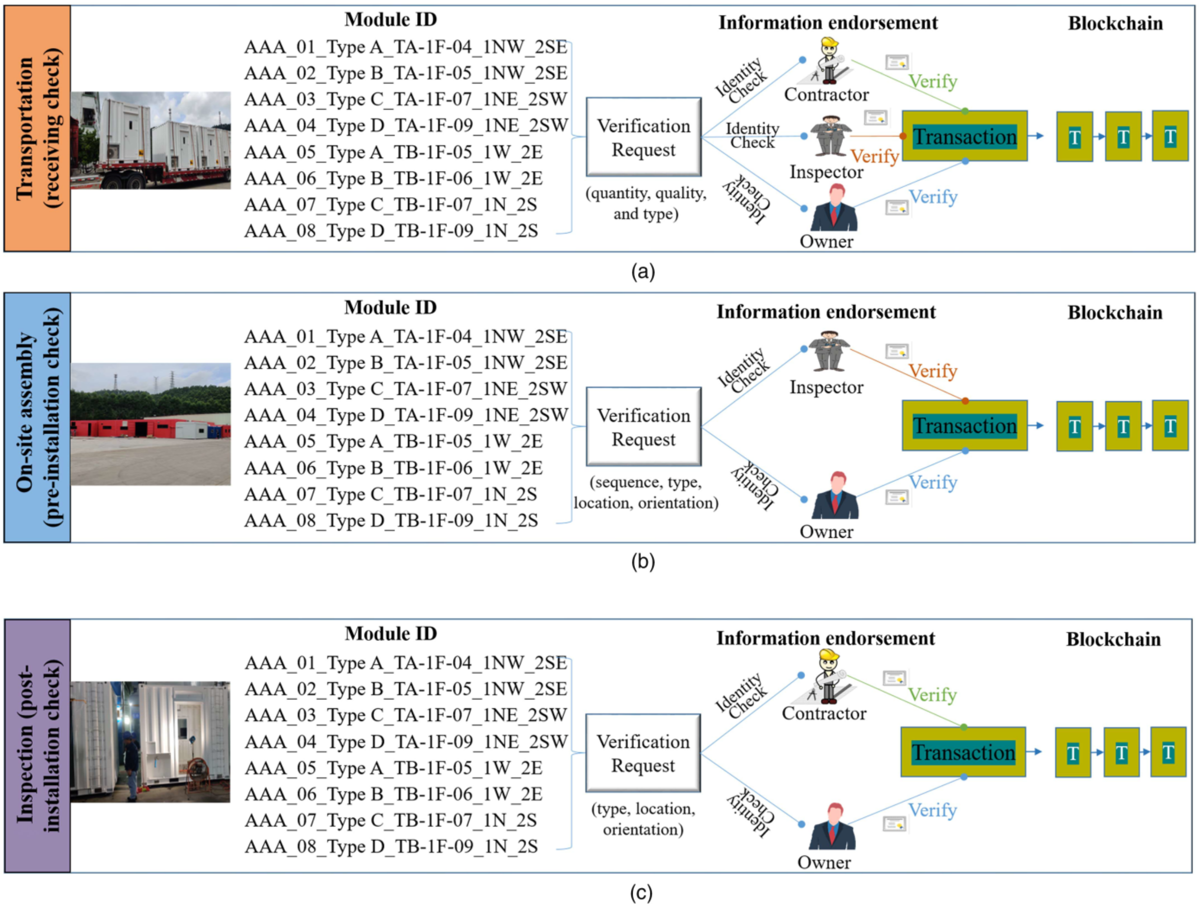


Fig. 9. Test scenarios: (a) module arriving; (b) pre-installation; (c) post-installation

In the second scenario, the operators of the contractor plan to install modules on the construction site (see Fig. 9(b)). The operator of the contractor sends out the request through the user interface to the managers of the inspector and the owner to verify the assembly sequence, type, location, and orientation of the modules before assembly starts. The managers of both the owner and the inspector crosscheck the transaction information with the assembly plan and endorse the transactions through digital signatures. After installation, in the third scenario, the inspector's operator inspects installed modules on the construction site (see Fig. 9(c)). The inspector's operator sends out the request through the user interface to the managers of the contractor and the owner to endorse the information about installed modules such as type, location, and orientation. Similarly, the managers of the contractor and the owner crosscheck the transaction information with their assembly operations records and verify the transactions through digital signatures. In all case scenarios, any shared information in the system was endorsed by the designated managers of the corresponding organizations to ensure its accuracy.

Interview results

Participants answered four interview questions after using the prototype system in the test. The responses are summarized in Table 4. In response to the first question on the advantages of the prototype system, all eight interviewees mentioned the potential of the prototype system to improve accuracy of information sharing. Three mentioned elimination or reduction of assembly rework issues. One participant from the contractor organization identified reduced labor costs due to reduced likelihood of re-installation. Three interviewees mentioned improved project performance. In addition, enhanced trust relationships among participants and increased motivation were mentioned as advantages of the prototype system by owner organization interviewees.

Table 4. Responses from interviewees

Interviewee	Response	Category
Question 1: What are the advantages of the prototype system?		
OW1	Enables a system for accurate and timely information sharing	1
OW2	May minimize inaccurate information sharing, which could decrease the chance of misplacement of modules	1, 2
	The system improves onsite assembly performance in the project.	4
OW3	May minimize asymmetrical information exchange, which could improve the trust relationships among participants	1, 5
OW4	Getting accurate information for the onsite assembly of modules will increase the motivation of the contractor.	1, 6
MC1	Accurate information sharing may minimize onsite assembly rework issues, which could decrease labor costs for the contractor.	1, 2, 3
MC2	Would improve information flow and minimize module displacement	1, 2
TR1	Enables accurate information sharing with project participants	1
	Would improve project performance	4
INS1	When assembly information is shared accurately, project performance could improve substantially.	1, 4
Question 2: What are the disadvantages of the prototype system?		
OW1	The system may incur additional development and maintenance costs for all parties	7
	Without a mature legal infrastructure, I think the system cannot be widely used in current modular construction projects.	8
OW2	If there are loopholes in the smart contract, the security of the blockchain network cannot be guaranteed.	10
OW3	The system will bring additional training costs to all parties.	7
OW4	Compared with the existing process, the system takes extra time for relevant parties to endorse the information through digital signatures.	9
MC1	If the scale of the project is large, the endorsement process will take too long.	9
MC2	I think we have to bear the cost of the system.	7
TR1	The endorsers have the opportunity to disclose project information (I know this is a very low probability event, but the impact is very high).	11
INS1	If the cost is too high, I don't think the participants will accept it.	7
Question 3: Would you use the prototype system? Why/Why not?		
OW1	I am not sure, maybe after the legal infrastructure for the system is ready.	Conditionally
OW2	Yes, as it could improve the accuracy of information sharing and reduce re-installation issues.	Yes
OW3	Yes, we have inaccurate information sharing all the time. The system would improve the current asymmetrical information-sharing issue.	Yes

OW4	Yes, I would. The system could motivate all to achieve accurate information sharing for efficient OAMC.	Yes
MC1	No. The information endorsement process is time-consuming and privacy issues may occur.	No
MC2	If the cost is known, I would use the system.	Conditionally
TR1	Definitely, yes.	Yes
INS1	Yes I would, but the cost has to be low.	Conditionally
Question 4: Do you have other suggestions to improve the prototype system?		
OW1	The system can be linked with BIM to assist the information endorsement.	12
OW2	The system should provide mobile-based applications to make it easier for participants to use.	13
OW3	I recommend testing the system in more projects to ensure its scalability.	14
OW4	The total cost of the system should be determined before its actual implementation.	7
MC1	I suggest sending text messages to participants to remind them to endorse the information.	15
MC2	I suggest a rough cost estimate for the system.	7
TR1	I do not have any suggestions.	-
INS1	The system should be tested in different projects to determine cost.	7

Responses to the second question on disadvantages of the prototype system are summarized in Table 4. Four interviewees mentioned additional costs for users such as development, maintenance, and training costs. One interviewee from owner organization mentioned lack of legal infrastructure as a disadvantage. An interviewees from the owner and contractor organizations referred to the relatively long time taken for users to endorse the information. Cybersecurity of blockchain and privacy were highlighted as a disadvantage by one interviewee from the owner organization and one from transporter organization, respectively.

In response to the third question about the users' willingness to use the prototype system, four interviewees said they would use the system without condition. One (from the contractor organization) opposed using the system because it may be time-consuming for large projects and present privacy issues. One interviewee from the contractor and the inspector organization stated that they would only use the system if the cost was low. One interviewee (from the owner organization) said he might use it after the required legal infrastructure is ready.

Interviewees made suggestions in response to the fourth question. Three interviewees suggested that the system cost should be determined before implementation. Interviewees from the owner organization suggested connecting the system with BIM to assist in information endorsement and developing mobile-based applications for the convenience of users. An owner organization interviewee also suggested testing the scalability of the system in more projects, while an interviewee from the contractor organization said that the system should be able to send text messages to participants reminding them to endorse information.

Discussion and Limitations

The scientific contribution of this study is summarized as follows. First, this research explores how blockchain technology can improve the accuracy of information sharing for OAMC. In a previous study (Lee et al., 2021a), blockchain was used to share and endorse virtual positioning information of prefabricated bricks. However, the potential of the consensus mechanism (CFT) in improving the accuracy of information sharing in OAMC has not been evaluated in an empirical study. Here, a conceptual model is presented for the application of blockchain technology in OAMC information endorsement. In the proposed model, the assembly information of each module is shared in a transparent way and endorsed by relevant parties before release, reducing the likelihood of disputes and bringing about a decline in assembly reworks. The Hyperledger Fabric-based prototype system shows the feasibility of the proposed model. Thus, this study may provide construction stakeholders with an innovative tool for information endorsement in OAMC. In addition, it can enhance stakeholders' understanding of the benefits of blockchain, which is an essential factor in the adoption of blockchain in actual modular construction projects. For practical implementations, configurable network components of the prototype system should be fine-tuned in terms of software (e.g., the endorsement policy) and hardware (e.g., CPU speed) aspects.

Second, the opinions of test participants on the use of the consensus mechanism of blockchain in OAMC for information endorsement are presented in detail, with advantages and disadvantages of the prototype system and user attitudes and suggestions summarized through structured interviews. Such analysis can facilitate understanding of barriers to the adoption of blockchain. Most importantly, since it is not feasible to address all the disadvantages and implement the suggestions simultaneously, understanding the actual user opinions of the prototype system can help to increase research attention and facilitate actual implementation of blockchain. The interview results can be reused to evaluate critical barriers with quantitative analysis methods like the decision-making trial and evaluation laboratory methods.

Third, the model provides a valuable reference for policy design of blockchain governance in construction, including relevant regulations, laws, policies, and standards. Policymakers can simulate information endorsement scenarios by using or further developing the prototype system. The proposed model is an adaptive structure that can expand in scope to facilitate supply chain management in construction projects and to include other participants, such as governmental supervision units, material suppliers, and manufacturers and subcontractors.

Despite these advantages, this study still has limitations. First, the operation transactions recorded onto the blockchain are manually input by humans. Manual operations may limit information sharing efficiency and introduce opportunistic behaviors (uploading tampered assembly information). Lee et al. (2021a) developed and tested an integrated digital twin and blockchain framework. The digital twin uses IoT sensors to update the BIM in near real-time, while the blockchain authenticates all transactions of the digital twin. Random errors and noise generated from IoT sensors can still result in a single point of failure for IoT networks, reducing data quality for BIM and negatively affecting the trustworthiness of the system. A recent study conducted by Lu et al. (2021b) explored smart construction objects (SCOs) as blockchain oracles to provide a data authenticity mechanism. Thus, future research can integrate the proposed model with BIM and the SCO-enabled blockchain oracles and test it in real-life projects. Second, the configured smart contracts have only been used for information exchange and block ordering services in the prototype system. Hamledari and Fischer (2020) and Das et al. (2020) adopted smart contracts to improve the certainty of construction contract payments. Therefore, future research can explore the combined application of the proposed model and smart contracts. Advanced technologies such as GIS (geographic information system) and 5G can also be integrated with the model to add more intelligence and autonomy to the OAMC management. Third, this study does not run a cost evaluation of running such a system, since the test scenario is limited to the mock-up stage of a modular construction project. Pradeep et al. (2021) suggested that cost and benefit analysis could be the next logical step when more empirical data is available. Fourth, only one pilot case study was carried out. Thus, testing results can only be perceived as a proof of concept of the model, rather than a final version for benchmarking performance or proof of compatibility to other OAMC projects. Future works are recommended to fine-tune the platform and test and evaluate it in other OAMC projects.

Conclusions

Successful delivery of onsite assembly in a modular construction (OAMC) project requires efficient communication and coordination by numerous stakeholders, who interact closely based on an array of information. However, sharing of inaccurate information may occur during OAMC, primarily owing to the widespread adoption of paper or paint labels, fragmented project-based organizations, and lack of information consensus mechanism. This study aimed to explore the use of blockchain technology to improve the situation of inaccurate information sharing in OAMC, starting with a theoretical exploration of how blockchain can truly help.

This study developed a blockchain-based model for modular construction to improve the accuracy of information sharing for OAMC. The proposed model was developed using a design science research (DSR) strategy to help project participants to endorse shared OAMC information. The model realizes information sharing endorsement processes via membership registration, information sharing-request, ordering service, consensus mechanism, and distributed storage. After that, a prototype system was designed to demonstrate the proposed blockchain-based model. The three key OAMC processes of arriving, pre-installation, and post-installation verification, are included to test the prototype system in the mock-up on-site assembly phase of a modular construction project. Finally, structured interviews were conducted with test participants to discover their opinions on the prototype system. The results show that the proposed model can improve the accuracy of information sharing for OAMC by allowing project participants to endorse information about the modules and their operations through the consensus mechanism, thereby reducing the possibility of onsite assembly reworks.

The limitations of this research provide opportunities for future research. One potential research direction is the blockchain "oracles" that connect the off-chain and on-chain world. For example, researchers can explore the use of decentralized smart construction objects to protect data uploaded to BIM and blockchain. In addition, future research can focus on the scalability evaluation of the proposed prototype system and its integration with smart contract payment, GIS, and 5G technologies. When more empirical data become available, the cost of the proposed system should be investigated in depth. Finally, the proposed model may extend to industries beyond the construction industry.

Data Statement

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

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