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RESEARCH ARTICLE

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Hyperledger fabric-based consortium blockchain for construction quality information management

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Abstract Lack of trust has been an ongoing issue for decades in construction quality management, hindering the improvement of quality performance. The development of mutual trust depends on immutable, traceable, and transparent construction quality information records. However, current information technologies cannot meet the requirements. To address the challenge, this study explores a blockchain-based framework for construction quality information management, which extends applications of blockchain in the domain of construction quality management. A consortium blockchain system is designed to support construction quality management in which participants' information permissions and lifecycle are discussed. Additionally, this study presents in detail the consensus process that aims to address the problem of information fraud. The automated compliance checking based on smart contracts is presented as well, aiming to assure that construction products meet regulation requirements. Finally, an example of the consortium blockchain network is visualized to validate the feasibility of blockchain-based construction quality information management. The research shows that blockchain can facilitate mutual trust in construction quality management by providing distributed, encrypted, and secure information records and supporting automated compliance checking of construction quality.

Keywords blockchain, construction quality, smart contracts, compliance checking, information management

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1 Introduction

Construction quality management is a collaborative process involving a large or small group of participants with different pursuits of interest. Lack of trust has been an ongoing issue for decades in the construction industry, hindering the improvement of construction quality. Mutual trust can improve the performance of construction quality management by helping smooth the construction process, increasing efficiency, and reducing management costs. Today, international contracting becomes common, and the complexity of the construction projects is increasing (Lau and Rowlinson, 2010). Apart from advanced construction technology, a collaborative and trust environment is needed to improve the quality performance of construction. However, current contractual relationships are mainly based on confrontational situations that reflect the low level of trust (Wang et al., 2017). Lack of accountability is the main factor damaging the trust and collaboration between participants (owners, supervisors, contractors, subcontractors, etc.). If who is primarily responsible for the quality failure cannot be determined, then organizations tend to find ways to cut corners and deflect blame from the resulting failures for pursuing illegal profits. Clear accountability depends on immutable, traceable, and transparent information records between participants.

The construction process generates a great amount of quality information that can be used in case of disputes and litigation among the numerous participants. With the adoption of digital technologies, construction management becomes increasingly fragmented and scattered. Information exchanges across organizations are much more frequent now than before. However, in terms of quality management, current information technologies cannot ensure the security, traceability, and transparency of the construction quality information that can be used in cases of quality disputes among numerous contributors in a project. Construction quality information may be tampered, which can lead to failures in quality accountability. Therefore, conventional information technologies are far from the accountability needs that are essential for higher levels of trust and collaboration in construction quality management.

Blockchain, also referred to as distributed ledger technology (DLT), is a disruptive technology that can create mutual trust in cooperation. The first application of blockchain is Bitcoin (Nakamoto, 2018). Essentially, blockchain is a simple database to store information. However, the decentralized and transparent property of a blockchain system enables the creation of a non-refutable record of data and real-time information sharing among various participants (Wang et al., 2020). These features make creating trust relationships easy. In the blockchain system, a participant of a project can access information, which is written through a consensus mechanism without relying on any central administrator so that no one has control over the data. The information in a blockchain is safe, which can be seen as strong evidence for quality disputes. Participants of the project do not need to develop trust relationships, which is difficult, because they can trust the blockchain itself.

In the construction industry, current research on the blockchain technology is in a fledging period. Few studies discuss the application of blockchain technology in the construction process, where it has the potential to make quality management more efficient, transparent, and accountable between all participants involved in the project. This study proposes a blockchain-based information management framework for construction quality management with the aim to improve the reliability, traceability, and transparency of construction quality information. Furthermore, this study investigates how smart contracts in the blockchain system can be used to enhance the automation level of compliance checking and show the related algorithms.

To summarize, the main contributions of this study are as follows. First, blockchain is a relatively new concept in the construction industry. This work is one of the first explorative studies to use blockchain to ensure the immutability, traceability, and transparency of construction quality information records. Based on the blockchain system, mutual trust can be developed between all participants involved in the construction quality management, which can indirectly reduce the coordination costs and enhance construction quality performance. Second, this study specifies the appropriate blockchain type for construction quality information management and discusses the participants of the blockchain system and their corresponding information permissions and lifecycle on the chain. In comparison, existing studies mostly qualitatively analyze the benefits of blockchain and ignore network modeling for its practical implementation (Turk and Klinc, 2017; Wang et al., 2017). Third, the consensus mechanism of the blockchain system is presented to show the transaction flows of the blockchain network. Moreover, based on smart contracts, automatic compliance checking on construction quality information is discussed, and an example of smart contracts is listed. Our work represents a small step toward exploring blockchain technology for construction quality management.

The remainder of this study is organized as follows. Section 2 reviews the literature and summarizes the blockchain research in the construction industry. Section 3 introduces the key concepts of blockchain technology and its potentials in construction quality management. Section 4 proposes a blockchain-based overall framework and discusses how to build a blockchain network for construction quality information management. Then, the transaction flow and compliance checking on the construction quality information is presented. Section 5 shows the application of the visualization system of the blockchain network. Section 6 discusses the limitations of blockchain technology as well as this work. Section 7 offers the conclusions.

2 Literature review

Trust among various participants can bring a high level of collaboration to the construction process, so it is widely seen as a key factor to project success, especially for improving productivity and ensuring construction quality (Love et al., 2011). Compared with engineering industries, construction projects are ephemeral; thus, organizations involved in a construction project find maintaining a long-term partnership difficult. The development of mutual trust among different organizations with divergent goals and objectives is a challenge (Manu et al., 2015). Mistrust may lead to individuals pursuing their own interests instead of the benefit of the overall project (Hunhevicz and Hall, 2020), which results in conflicts between project teams and damages the performance of construction quality. Improving information sharing between parties can facilitate the development of mutual trust and collaboration in a construction project that is why Building Information Modeling (BIM) is prevailing in the architecture, engineering, and construction (AEC) industry. For instance, Oh et al. (2015) proposed a BIM-based system for collaborative design, which can support the collaboration of architecture and mechanical, electrical, and plumbing (MEP) design with enhanced quality and efficiency. Singh et al. (2011) proposed a theoretical framework where BIM is used as a multi-disciplinary collaborative platform to enable better collaboration in the construction process. Chen and Luo (2014) pointed out that the potential of BIM lies in its ability to present and integrate multi-dimensional data, and investigated how BIM can fit into construction practice. Ma et al. (2018) developed a system integrating BIM and indoor positioning technology to make the process of construction quality management more effective and collaborative. However, simply relying on BIM or traditional information management systems is not enough when aiming to truly achieve trust, because both of the two cannot guarantee intellectual property and cybersecurity (Solihin and Eastman, 2015), blurring the level of responsibility between different project teams (Arensman and Ozbek, 2012).

Blockchain technology provides a creative means to achieve mutual trust by offering immutable, transparent, and traceable quality information records that can be used in responsibility allocation of quality failures. Information asymmetry can also be addressed because all participants have the same information records in a blockchain network. Organizations cannot deflect blame from the resulting failures when they broke the rules, such as cutting corners. The history of blockchain technology can be classified into three stages: Blockchain 1.0, 2.0, and 3.0 (Swan, 2015). Taking Bitcoin as a typical application, Blockchain 1.0 is used for cryptocurrencies as a model of securely validating and storing information of transactions (Dimitri, 2017). With the adoption of smart contracts, the era of Blockchain 2.0 was initiated in which the usage of blockchain focused on the economic, market, and financial applications. A smart contract is defined as a computerized transaction protocol that executes the terms of a contract, which can enable more complex transactions and strengthen mutual trust between users (Chamber of Digital Commerce, 2016). Smart contracts are encoded by computational programming languages and then get deployed and executed automatically in blockchains. Blockchain 3.0 expanded the application of blockchain to other industries, which aims to provide a new paradigm for organizing social activities with less friction and more efficiency (Wang et al., 2017). Blockchain 3.0 has the potential to change the way applications are developed, create efficiencies, and drive digital transformation in many, perhaps all, industries (Mathews et al., 2017), for example, logistics, healthcare, and energy (Fan and Zhang, 2019; Helo and Hao, 2019; Zheng et al., 2019b).

Blockchain 3.0, as a disruptive technology, has also piqued the interest of researchers in the whole AEC industry. Li et al. (2019) identified seven categories of blockchain applications in the built environment: Smart energy, smart cities and the sharing economy, smart government, smart homes, intelligent transport, BIM and construction management, and business models and organizational structures. Wang et al. (2017) proposed three types of blockchain-enabled applications in the construction sector: Contract management, supply chain management, and equipment leasing. San et al. (2019) presented the potentials of blockchain in the construction industry, namely, contract management, electronic document management, building information modeling, property management, supply chain management, and funding management. Considering the backward nature of the construction industry in digitalization and its reticence to change, Perera et al. (2020) discussed whether blockchain is pure hype or real, and pointed out that blockchain indeed has a credible potential in the construction industry in property management, construction management, asset management, and so on. These studies summarize potential applications of blockchain technology in the construction industry and provide a roadmap for blockchain research in the construction industry. However, they primarily investigate those applications from a qualitative perspective.

Recently, a small number of studies have started to explore how blockchain can solve specific problems in the construction industry. Table 1 shows the current research articles that discuss the specific application of blockchain in the construction industry from the aspects of supply chain management, contract management, and integration with BIM. For example, blockchain can ensure that supply chain information is traceable while increasing efficiency and securing more confidence that the construction materials are genuine and of high quality (Kshetri, 2018). Similarly, blockchain can solve the challenges of BIM implementation in practices, such as poor intellectual property and cyber safety (Solihin and Eastman, 2015), fuzzy responsivity, and contractual relationships (Redmond et al., 2012), by providing immutable, transparent, and traceable information records about BIM model. Nawari and Ravindran (2019) presented an overview of blockchain and its applications in the AEC industry as well as its potential integration with the BIM process concerning network security, data storage and management of permissions, and data ownership, thus enhancing the framework for automating the construction design review process, such as smart contract technologies and Hyperledger Fabric (HLF). Moreover, the smart contract is self-executing, so it can embed a blockchain-based platform into the project execution practice. Regarding construction contract management, Wang et al. (2017) suggested that the blockchain-enabled smart contract can be stored in a non-editable format, together with the self-executing codes, so that neither party has the upper hand to tamper or prevent the execution of the contract. Therefore, it can be used to eliminate payment issue, improve the efficiency of the contract administration process, and reshape the trusting behavior from the human trust to coding trust.

In summary, blockchain technology is still in its infancy given the lack of empirical studies within the construction context. Potential applications mainly depend on the fact that blockchain can provide tamper-proof information records, ensure real-time information sharing and synchronization among different parties, and achieve automated execution supported by smart contracts (Helo and Hao, 2019). These benefits can also solve the issue of lack of accountability in the construction quality management by providing immutable and transparent quality information records among stakeholders. Clear accountability is the foundation of mutual trust in the collaboration, which can improve construction quality and efficiency. Construction projects involve a great number of participants. For example, the Crossrail project in London had more than

Table 1 Specific applications of blockchain technology in the construction industry

Research field in construction	Specific applications	Reference
Supply chain management	A blockchain-based framework was proposed to solve the challenges of information management in the precast supply chain, such as fragmentation, poor traceability, and lack of real-time information, and the performance of the framework was evaluated with a case study	Wang et al. (2020)
	The potential application of blockchain in logistics of construction materials was discussed by integrating with radio frequent identification (RFID) technology, in which an example of manufacturing and delivery of ready-mixed concrete was given	Lanko et al. (2018)
Contract management	Considering delays in construction payments, a blockchain framework was developed to host smart contracts related to construction payment and to automate payment actions after achieving consensus among the relevant project stakeholders	Luo et al. (2019)
Integration with BIM	A framework combing blockchain with BIM was proposed for sustainable building design coordination and collaboration in multiple building life cycle stages and to solve the challenge of BIM in intellectual property and legal responsibility	Liu et al. (2019)
	A cup of the theory was developed to represent the integration of BIM, Internet of Things (IoT), and blockchain, which can be used to design an efficient building maintenance system	Ye et al. (2018)
	A new conceptualized framework resulting from the integration of blockchain and BIM processes was proposed to improve the efficiency of building permit processes in post-disaster events in which the smart contract and HLF were discussed	Nawari and Ravindran (2019)

700 various suppliers just from the UK, and the Burj Khalifa project involved over 12000 workers from more than 100 countries on site at the peak of its construction (Penzes, 2018).

However, few studies focus on the potential application of blockchain in quality information management. Therefore, the present study aims to explore how blockchain technology can be used to support construction quality management by providing immutable and transparent construction quality information records.

3 Blockchain concepts and its potentials in construction quality information management

3.1 Key concepts and technologies of blockchain

In the blockchain system, construction quality information is stored in blocks. The data structure of a block is shown in Fig. 1, which contains two parts: Block header and block body. The block header has various parameters, such as the index of the block, the hash value of the parent block, the hash value of the block, timestamp, nonce, and Merkle root. Merkle root is a final value obtained by multiple hash operations, showing the numerous transaction records of the block in the form of a binary tree, and it is used to verify whether the transaction data of this block has been tampered with. The block body contains a set of transactions that represent the original information to be transferred into hash value based on the hashing algorithm. In Fig. 1, "Block *n*" contains eight transactions.

Blockchain involves a combination of technologies, including peer-to-peer protocols, hashing algorithms, consensus algorithms, and smart contracts. In a peer-to-peer network, no peer is superior to others, and all nodes share the burden of providing the required network services (Kaushik et al., 2017). Therefore, all participants have safety information records if they are in the same blockchain network. All the nodes are connected on a flat topology without a hierarchy, central authority, or main server, making the peer-to-peer network purely decentralized. Therefore, a consensus mechanism is used to ensure that the block is valid before it is recorded on the ledger. In the blockchain, consensus algorithms are used to approve and confirm transactions in the distributed environment through a series of procedures, such as Proof of Work (PoW), Proof of Stake (PoS), Practical Byzantine Fault Tolerance (PBFT), Delegated Proof of Stake (DPoS), and so on. Supported with consensus mechanism, once transactions are added as a block to the distributed ledger, all ledgers reflect this change that all participants share a copy of the ledger. Hashing algorithms are used to ensure the security of information stored in blocks by transferring the traditional information into hash values. A blockchain (or a ledger) can be regarded as a linked list of blocks. Each block contains two parameters: The hash value of the current block and the hash value of the previous block (also referred to as the parent block). Nofer et al. (2017) highlighted that the hash values are unique, and if any change is made to a block in the chain, the respective hash value is changed immediately. Therefore, if an attacker attempts to change one hash, then the hashes in the entire chain between the tampered block and the latest block need to be changed, which is impossible in the distributed environment. The smart contract is another essential technology in the blockchain. Smart contracts are programmatic objects that can self-execute terms of a

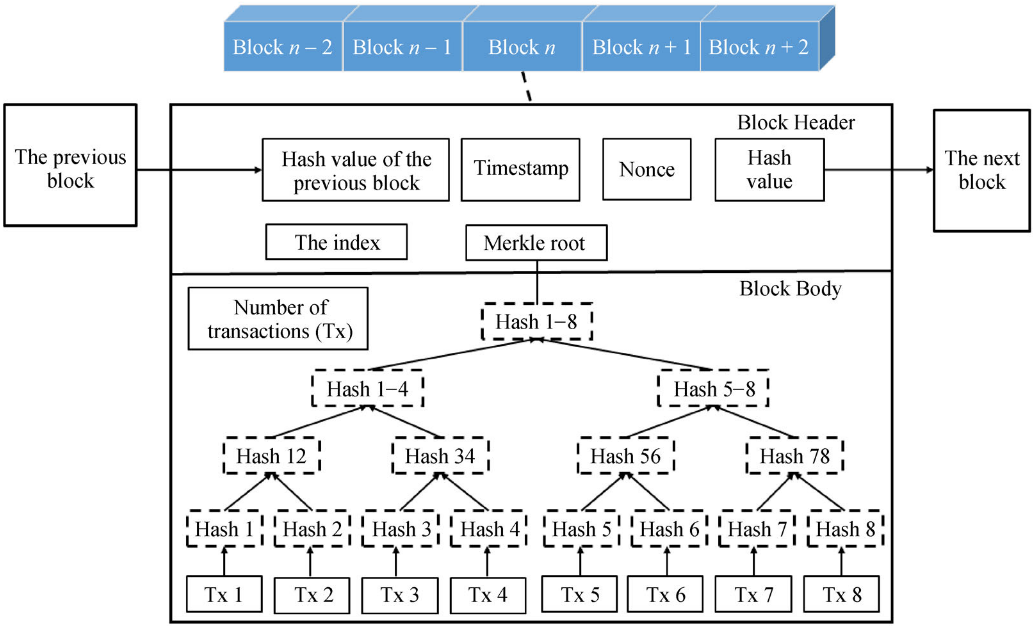

Fig. 1 Data structure of blocks.

contract upon the fulfillment of certain conditions. In the blockchain system, once the smart contracts are successfully deployed, no one can change the items, and it can continuously monitor data changes on the blockchain or external data source and automatically execute when the conditions are met. Therefore, smart contracts remove the requirement of a third-party intermediary for overseeing the transaction in real time, which can reshape the trust model from human trust to coding trust. A smart contract contains the trigger conditions for responses and actions that need to be performed after the trigger, as shown in Fig. 2. Smart contracts enable digitization and automation of executing business workflows, which then facilitates the development of blockchain-based Decentralised Applications (DApp) (Li et al., 2017).

3.2 Potentials of blockchain in construction quality information management

In the construction process, every link of the responsible part in on-site construction can be an issue for information sharing and trust erosion. Traditional information management methods cannot provide an open and trustworthy information record and lack transparency and traceability, which hinder the collaboration quality between participants and affect the construction quality. Blockchain has the potential to tackle these challenges and improve trust in construction quality management.

As mentioned in the literature review, blockchain technology has various merits in information management, such as transparency (Badzar, 2016), information sharing (Wang et al., 2017), traceability (Wang et al., 2020), and reliability (Kshetri, 2018). Figure 3 shows the benefits of applying blockchain in construction quality management. Construction quality management involves a great number of participants, for example, owners, contractors, supervisors, various subcontractors, and suppliers. The complexity often causes some participants to deceive others and cut corners to pursue their interests. Moreover, the non-transparent quality information records may be tampered, making judging who should be responsible for the quality failure difficult, which leads to distrust in the

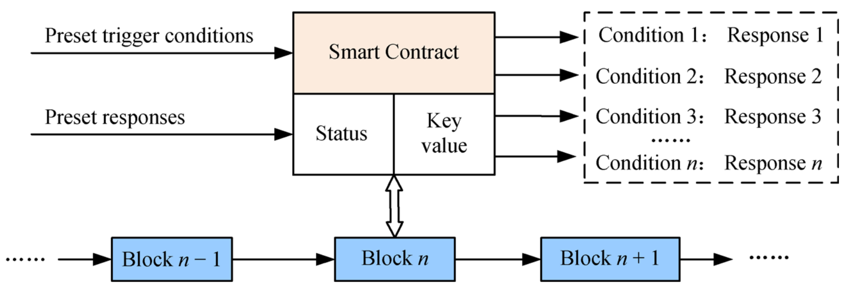

Fig. 2 Structure of smart contracts.

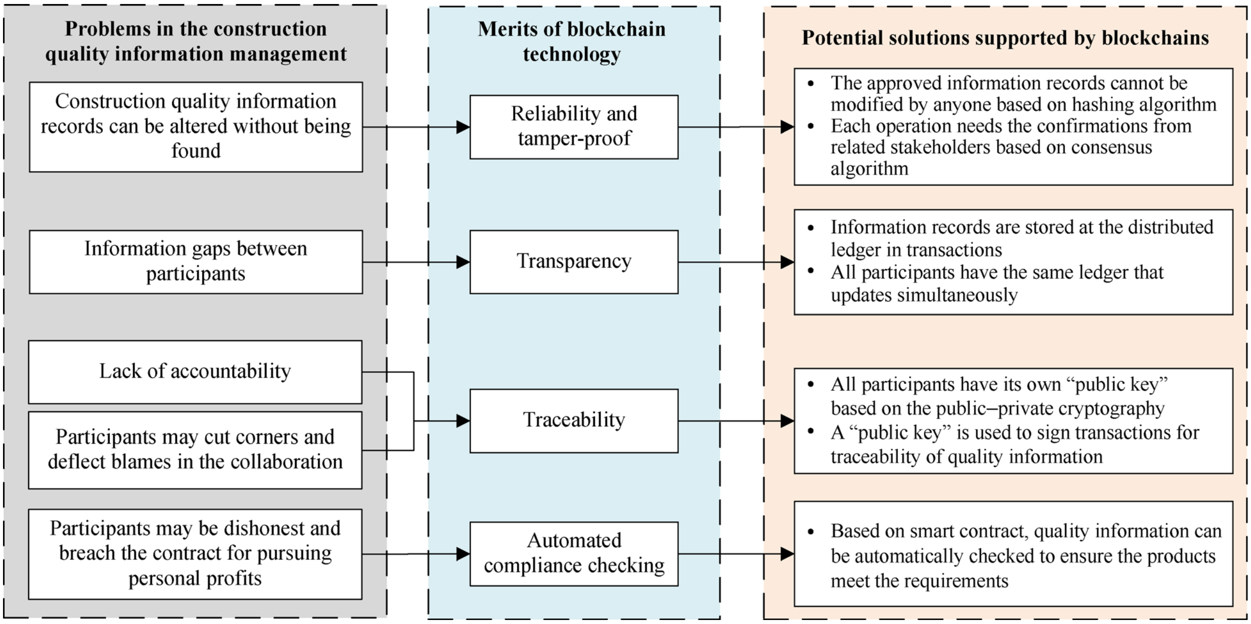

Fig. 3 Merits of blockchain technology in construction quality information management.

collaboration and then affects efficiency and productivity. The blockchain technology can solve these problems by storing construction quality information in the blockchain network. In addition, smart contracts can be automatically executed when a series of preconditions are met. This characteristic can be used to achieve automated compliance checking in the quality acceptance process. When the construction of an inspection batch is finished, the construction quality information data can be checked by the smart contract that reveals the regulation information to assure construction quality. It improves efficiency and reduces the cost of quality management. In this study, we propose a framework to further explain how the blockchain manages the construction quality information to facilitate the development of mutual trust among various shareholders.

4 Blockchain-based construction quality information management

4.1 Overall framework for construction quality information management

As shown in Fig. 4, a blockchain-based framework for construction quality information management is proposed aiming to ensure that construction quality information is immutable, traceable, and transparent between various participants. The framework contains three parts: The blockchain, BIM, and IoT module. The blockchain module has the core role, which is used to record the construction quality information in the construction process. Blockchain module is referred to as the "information database" in the framework, which aims to solve the problems of information authenticity and information sharing simultaneously (Huang et al., 2020).

BIM module is perceived as the "information platform" in the framework, which can integrate and visualize the construction information from various parties and stages. BIM can present and integrate multi-dimensional information for blockchain (Chen and Luo, 2014). BIM is widely used to facilitate information sharing between different stages and participants in AEC industry. Although BIM adoption has come a long way in the past decade, it has yet to reach its full potential in construction management. Foster (2008) claimed that BIM may bring difficulties in assigning responsibilities and liabilities. Cubitt and Coldwell (2014) warned the issues of intellectual property, traceability, and confidentiality of information in BIM. Blockchain technology can help BIM solve these problems. The benefit of the integration of these two technologies can be confirmed in recent literature. Ye et al. (2018) proposed the Cup-of-Water theory. BIM is the cup bottom for holding the digital information of the whole building lifecycle, and blockchain is the cup wall for ensuring the high-value, single source of truth. Liu et al. (2019) claimed that the characteristics of the blockchain (e.g., decentralization, traceability, information sharing, and prohibition of tampering) can help BIM better integrate information and establish clear responsibilities. A combination of BIM and blockchain has the potential of serving as a platform for true collaboration in construction (Mathews et al., 2017). Noteworthily, the sufficient integration of BIM and blockchain should depend on BIM 3.0 rather than BIM 2.0 (Heiskanen, 2017). BIM 2.0

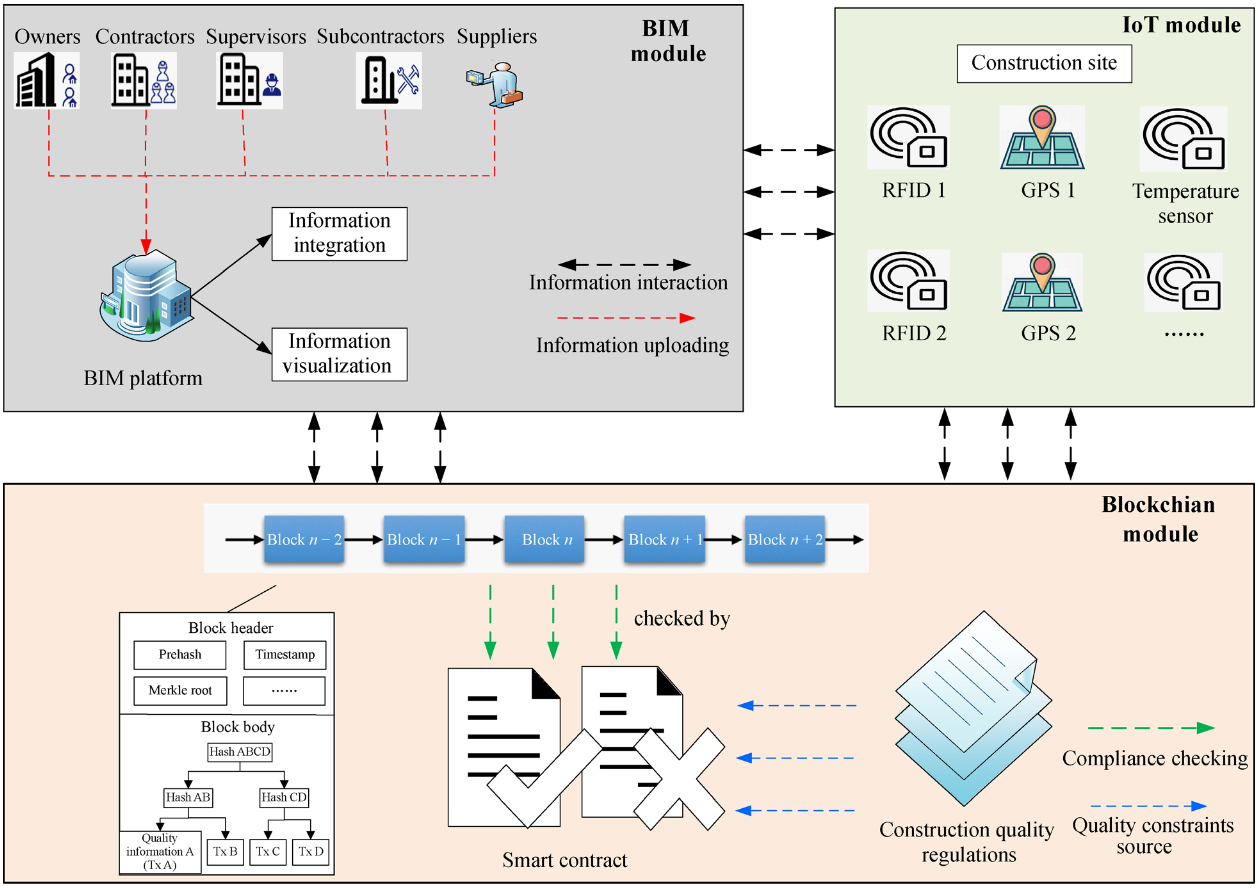

Fig. 4 Blockchain-based framework for construction quality information management.

means a collaborative way of working, in which 3D models with the related information are created by separate discipline models (Kassem et al., 2016), whereas BIM 3.0 means fully open process and data integration enabled by web service based on some standards, such as Industry Foundation Classes (IFC) and buildingSMART Data Dictionary (bsDD) (BIM Dictionary) (McPartland, 2014). Linking the information- and data-rich BIM 3.0 environment with the digitized, immutable, and transparent blockchain can provide a wide range of solutions on quality accountability and mutual trust. Therefore, we combine these two technologies into the overall framework.

Additionally, in this framework, the IoT module is adopted as an essential “information source”, which aims to automatically collect the construction quality information by sensors. For example, RFID sensors have been widely used in construction sites to collect information on labor, equipment, or materials. Doing so can avoid the possibility of data errors due to the human factor or intentionally false information. However, due to the current centralized sensor system, the central database is vulnerable to attacks. Blockchain can solve this problem and ensure the security of the information. Moreover, the information collected by sensors seems to be the trigger condition of smart contracts in the blockchain system. For example, temperature sensors need to upload the temperature information if a smart contract states that when the temperature of the construction site is higher than 40° centigrade, then the client should pay a certain amount of dollars (allowance) to the construction contractor.

Through the combination of these three modules, a blockchain-based system can be developed for construction quality information management, wherein visual evidence of construction quality information is written into a ledger, timestamped, gathered, and locked into a block through consensus, visible for the participants. The construction quality information is exported from the BIM system and then stored in the blockchain system. In the blockchain system, these information records are transparent and immutable between various participants. Additionally, automated compliance checking can be achieved by smart contracts in the blockchain network to assure the construction quality meets the requirements in the construction quality regulations. The process of compliance checking based on smart contracts is introduced in Section 4.3.2.

4.2 Consortium blockchain network for construction quality information management

To achieve mutual trust in business cooperation, organizations involved in construction quality management should have the same and reliable quality information records that are used as the basis of quality accountability. Therefore, the construction quality information is transformed into transactions stored in the blockchain system in the overall framework. We should determine the appropriate blockchain type for storing construction quality information and choose the corresponding platform for the development of the blockchain network. Currently, there are three types of blockchain systems based on the level of openness and access, namely, public, private, and consortium blockchain (Morabito, 2017).

1) Public blockchain: This completely decentralized blockchain is not controlled by anyone. Anyone can join as a new node and perform operations, such as reading historical data and submitting transactions. The risk of receiving attacks is low, but the executing efficiency is also low due to the long time required to validate and complete transactions (Zheng et al., 2019a). The most popular examples of public blockchains are Bitcoin and Ethereum.

2) Private blockchain: In contrast with the public blockchain, the write rights of private blockchain are entirely in the hands of an organization, so all the nodes involved in the chain are strictly controlled. Private blockchain is also referred to as "permissioned blockchain", emphasizing data privacy, which is limited to user access within an enterprise. Typically, this type of blockchain is common in an internal system or network in an enterprise, especially in financial and auditing systems.

3) Consortium blockchain: In this type of blockchain, several organizations or enterprises participate in the management of the blockchain network. Each organization or enterprise controls one or more nodes (referred to as peers in the chain), and they record transaction data together. Read-write access permission can be controlled because the consensus process is controlled by preselected nodes on this chain. In most cases, it is used in business to business scenarios, such as interagency transactions, settlement, and liquidation.

These three types of blockchain are all based on consensus mechanisms to ensure the security and reliability of information management, i.e., traceable and nontamperable, but they also have significant differences to meet different types of application requirements. Table 2 compares these three blockchain types. From the public, consortium to private, the degree of decentralization has gradually decreased, and the scope of central control has been expanding (Zheng et al., 2019a). A consortium blockchain balances the advantages of "decentralization" and "high efficiency", exhibiting merits of being partially centralized and able to control data and keep privacy as each party requires (Turk and Klinc, 2017). On this chain, read-write access permission can be decided by consensus process controlled by preselected nodes, so information is made available to only those participants that are authorized. Additionally, consortium blockchain can provide a complete series of functions, such as certification, authorization, and auditing of the participating members, which can meet the requirements in business cooperation. Construction quality management involves different organizations, and only the authorized members of the project can join the blockchain network. Between the collaboration processes, different parties may have different requirements regarding the control over information and privacy. Subsets of organizations can have their channels to communicate and can have isolated information only for respective associations. For example, contractors can create different channels for different business cooperation with different subcontractors, which can ensure the privacy of the information. Therefore, the consortium blockchain is selected for construction quality information management.

To develop a consortium blockchain, the Hyperledger Fabric (HLF) platform is adopted as it is suitable for complex construction industry transactions and business requirements. Hyperledger is a project hosted by the Linux Foundation in 2015 that aims to develop blockchain technologies for business use cases, and HLF was among the first projects emerging from Hyperledger in 2016. In a fabric network, participants (called peers) can form various channels. Each channel has a ledger, which only can be accessed by the members of this channel. Smart contracts, called chaincode in HLF, are programs, installed by the

Table 2 Comparison of three types of blockchain

Type	Decentralized degree	Access mechanism	Transaction cost	Transaction speed	Application scenarios	Example
Public	Complete decentralization	Anyone	High	Low	Digital currency	Bitcoin, Ethereum (ETH)
Consortium	Partial decentralization	Authorized organizations or groups	Medium	Medium	Business cooperation	Hyperledger, R3 Corda
Private	Centralized	Specific individuals or entities	Low	High	Financial and auditing institutions	Arcblock

peers that provide controlled access to the ledger. As shown in Fig. 5, a consortium blockchain network is proposed for managing construction quality information based on the HLF platform, which involves contractors, owners, supervisors, subcontractors, and government. In a specific construction project, these participants should be in one channel, which aims to ensure they share the same information records named ledger. These participants can set up one or more peers and enter the blockchain network system through the client. Worthy of noteworthy is the different lifecycles of different participants of a project on a chain. Specifically, the subcontractors exit the blockchain system once they finished the contract task. If the participant is out of the channel of the chain, they cannot access to the construction quality information ledger. The government peer is always on the chain to store and query the construction quality information. Once the subcontractors are involved into construction quality disputes even after they have exited the blockchain system, the government peer can help them to query the related information records in the ledger. Table 3 shows the lifecycle and permission of different participants on the chain.

Table 3 Participants' permissions and lifecycle on the consortium blockchain

Participants	Permissions	Lifecycle on the chain
Government	Query	Always on the chain
Contractor	Query Upload	Contractors would be always on the chain; Subcontractors would exit the chain when the contract tasks are finished
Supervisor	Query Compliance checking	Always on the chain
Owner	Query Confirm	Always on the chain

4.3 Construction quality information management on the blockchain

4.3.1 Transaction flow of blockchain network based on the consensus process

In the blockchain network system, the information is transformed into transaction proposals that need to reach a consensus agreement generated by predefined peers (also referred to as endorsing peers) before they are added into the ledger. The consensus process on the HLF platform consists of three steps: 1) transaction proposal and execution, 2) ordering transactions, and 3) validating transactions, which can ensure that the ledger is shared, unchangeable, and immutable throughout its life. A transaction operation needs to be conducted when the construction of an inspection batch is finished. The consensus process of uploading construction quality information is shown in Fig. 6, in which there are three participants: Contractors, owners, and supervisors.

First, in this case, the contractor peer needs to submit the transaction proposal via the client application to the endorsing peers, that is, the owner peer, contractor peer, and supervisor peer. The transaction proposal contains the construction information of this inspection batch that can be exported from the BIM system. Then, these endorsing peers check the validity of the transaction proposal and send back their response to the proposer with their signatures. The endorsement policy varies in different cases, which is decided by the smart contract. Specifically, the quality of the inspection batch constructed by contractors is a responsibility of contractors, owners, and

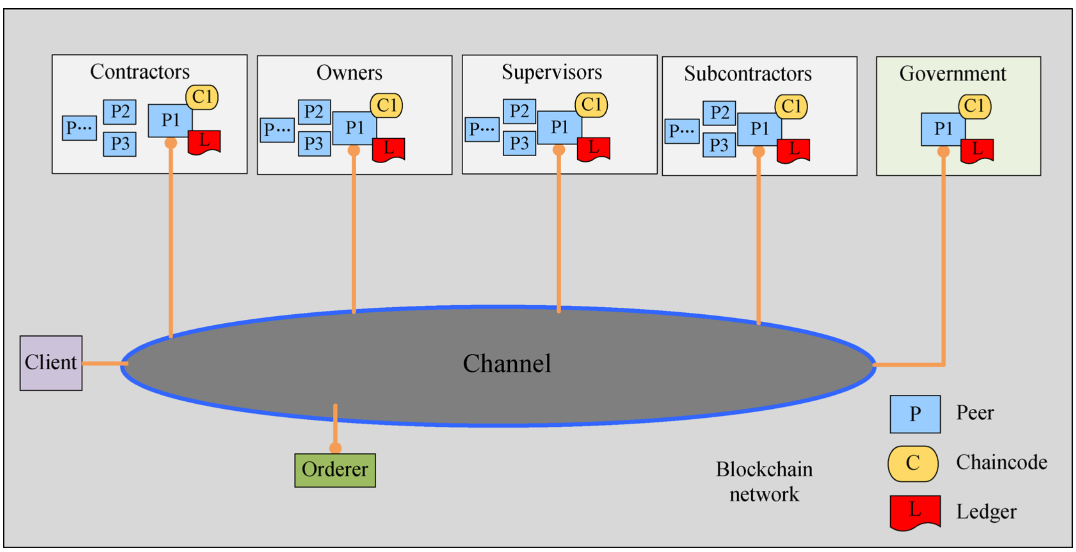

Fig. 5 Consortium blockchain network based on HLF.

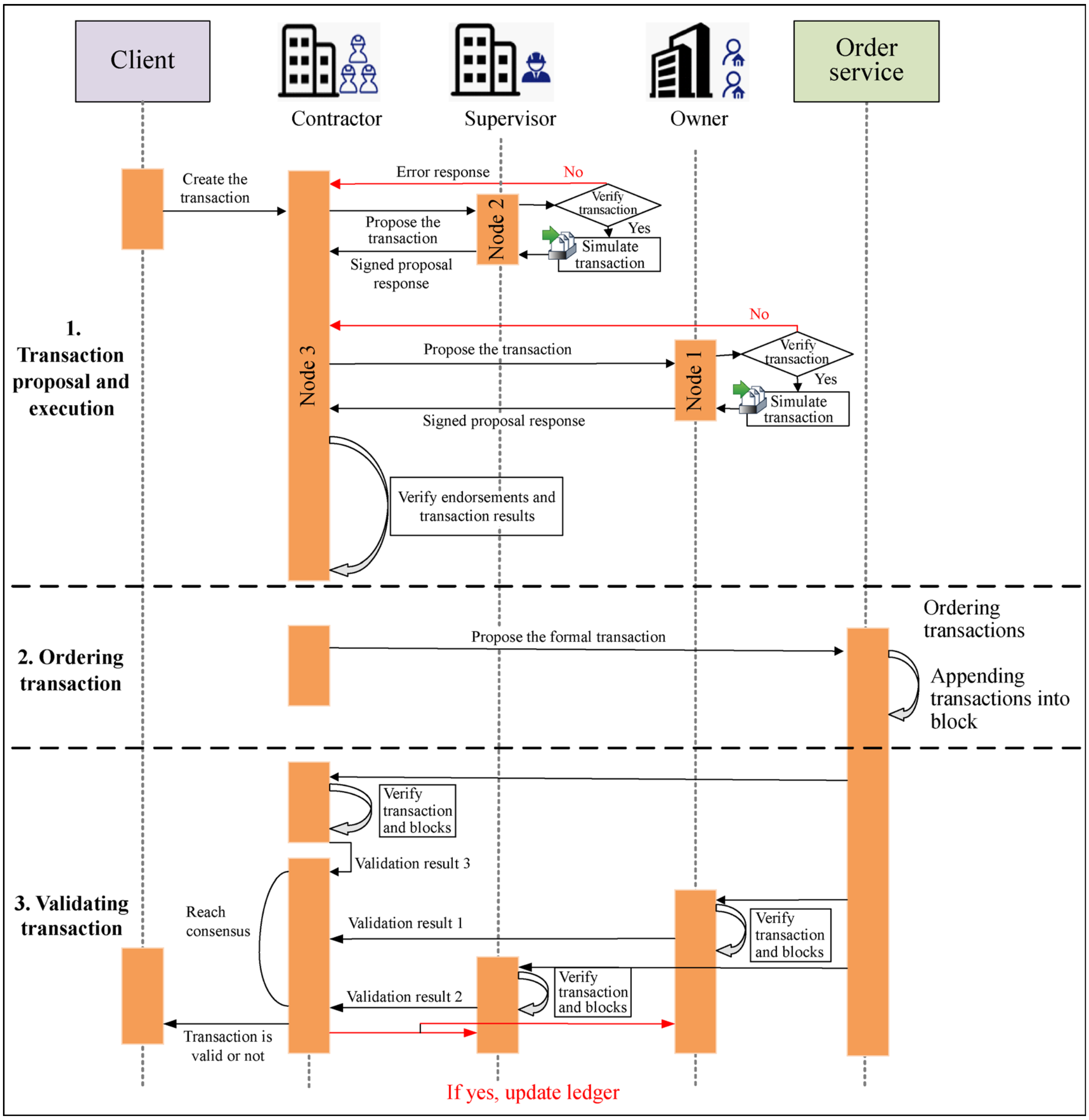

Fig. 6 Transaction flow in the consortium blockchain network based on the consensus process.

supervisors. For this reason, these peers are endorsing peers in this case. In addition, the ledger is not updated at this point, and this process can be regarded as a simulation of executing the transaction to verify whether the proposer (the contractor peer) is properly authorized to perform the proposed operation, the format of construction information is right, the content of construction information has been submitted, and so on. With the confirmation from all relevant stakeholders, the authenticity of a transaction can be remarkably improved, which can avoid fraud and improve mutual trust. The initial transaction proposal with the endorsing peers' signature is referred to as "proposal response", which will be sent back to the client.

Second, the client will check the "proposal response" to judge whether the endorsement policy has been followed. Subsequently, the "proposal response" is assembled as a formal transaction for the ordering service, where all transactions from all applications during a certain time period are ordered. The order service peer orders transactions chronologically and collects them into new blocks by channel according to a specific ordering algorithm.

Third, the block containing the transaction is broadcast to all peers so that they can validate the transactions. Each transaction is tagged as valid or invalid by each peer. If the transaction proposal is valid, then the ledger will update. All peers are informed that the construction information of this inspection batch is added to the blockchain, and, at this time, the information is no longer editable.

Based on the consensus process, all inspection batches' construction information are stored in the consortium blockchain system when the construction of the inspection batch is finished. Once these information records are stored in the blockchain system, they are immutable and transparent among various participants, which can help stakeholders with various incentives to reduce coordination costs and promote the construction process to be more efficient, transparent, and accountable (Penzes, 2018). When the construction information of the inspection batch is stored into the consortium blockchain system, compliance checking is performed to judge whether the inspection batch meets the quality requirements. Notably, the checking result information is also stored in the consortium blockchain system, which can reveal the process of construction quality management. These two types of information are collectively referred to as construction quality information.

4.3.2 Construction quality compliance checking based on the smart contract

Based on the blockchain system, construction quality management is fully implemented in the basic unit — the inspection batch. When the construction of an inspection batch is finished, the corresponding construction information is uploaded in the blockchain system. Then, the compliance checking process is invoked to check the inspection batch according to regulations to assure the construction quality, which is called construction quality compliance checking.

Compliance checking is important to ensure the construction quality, especially in China, where construction workers have not yet been industrialized. Most of the workers on the construction site are migrant workers with high mobility, and most of them have not received professional skills training. However, in construction practices, quality compliance checking is always conducted when the whole construction of subprojects is finished and cannot be carried into the construction process. Construction quality compliance checking is still a labor-intensive and costly manual task that hinders the delicacy management and, therefore, affects the performance of construction quality. Some subcontractors may tend to cut corners to pursue their own interests when the compliance checking cannot be implemented in each inspection batch. In addition, manual compliance checking is subject to the personal ability and responsibility of inspectors.

Automated compliance checking can avoid these limitations by extracting the quality constraints first. For example, Eastman et al. (2009) reviewed building code knowledge modeling and automatic rule-based checking (although dedicated to building design domain). Macit İlal and Günaydın (2017) studied the computerized representation of building codes for realizing automated compliance checking. Zhang and El-Gohary (2016) proposed a new approach for automated information extraction from building codes, which combines semantic modeling and natural language processing (NLP) techniques. Zhou and El-Gohary (2017) developed an ontology-based algorithm to support fully automated energy compliance checking. These quality constraints regulated in construction quality regulations can be extracted and then be encoded into smart contracts in the blockchain system. Smart contracts can support automated compliance checking. Zhang et al. (2018) proposed that smart contracts can define operations on the information and provide seamless services to the application users. Essentially, smart contracts are written as computer codes representing specific business logics. In this case, business logics mean the quality constraints in the regulations. Smart contracts enable the blockchain system to be a lightweight DApp for construction quality compliance checking, which has the following advantages:

1) Construction quality compliance checking can run autonomously without the assistance of a third party and thus avoid subjectivity and improve efficiency. When the construction quality information of an inspection batch is uploaded in the blockchain system, the corresponding smart contract is invoked and compliance checking is enforced, and no one can interfere with the process. The construction quality management is implemented into a basic unit — inspection batch.

2) The outcome of compliance checking is recorded and easily traceable in the blockchain system because all operations have the digital signature of the responsible person. These outcomes are immutable, and the compliance checking process has a higher level of transparency.

Figure 7 shows the construction quality compliance checking in the blockchain system when an inspection batch named reinforcing cage is constructed by main contractors.

1) At the beginning of compliance checking, a project participant, the contractor in this case, submits the construction quality information of the reinforcing cage and requests for compliance checking on the client. After the consensus process, the initial construction quality information is stored in "Block *n*". Notably, when a contractor submits a request for compliance checking, it means that the contractor has completed the self-inspection process and is responsible for the result of self-inspection.

2) When the supervisors receive the request, this peer read the content in "Block *n*" on the client and invoke the related smart contracts to perform the compliance checking on the construction quality information of the reinforcing cage. The pseudocode of the chaincode is shown in Fig. 8. The process of compliance checking is fully automated. If the compliance checking is qualified, then the supervisor submits a request for quality acceptance to owners. Otherwise, the supervisor submits a request for repairing to construction contractors. The result of compliance checking and the initial construction quality information of the inspection batch are stored in "Block $n + 1$" after the consensus process.

3) When the owner receives the request from the

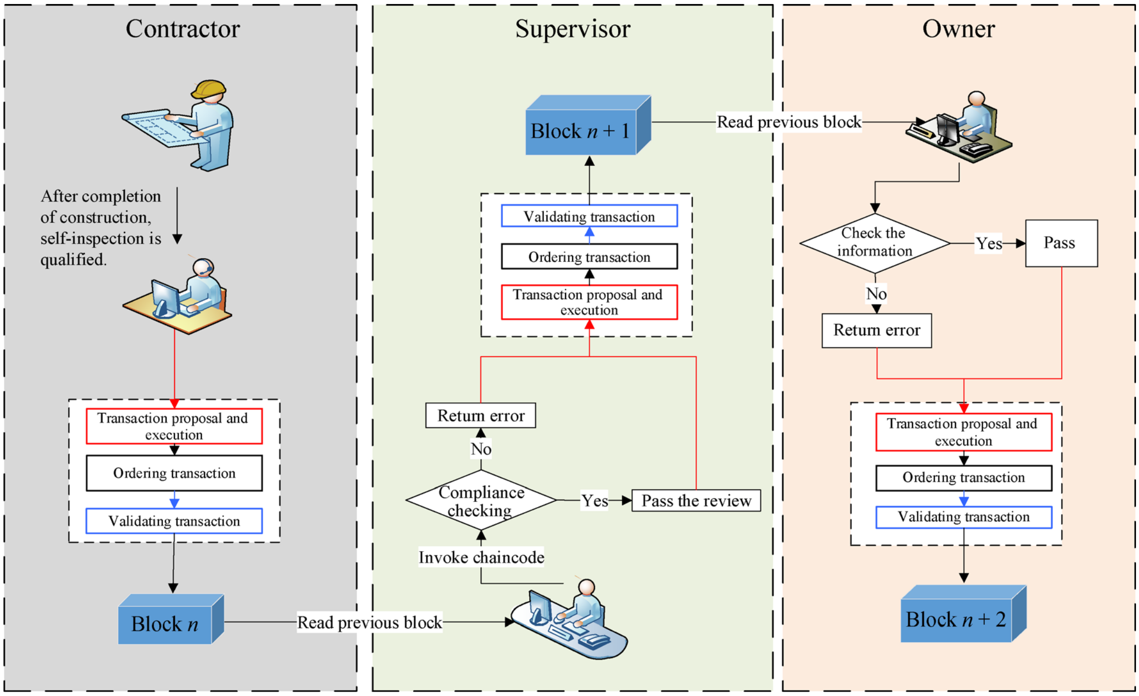

Fig. 7 Construction quality compliance checking in the blockchain system.

```
#Define parameters of SpacingofMainBars, Length, SpacingofStirrup, Diameter #
Def get_default (SpacingofMainBars, Length, SpacingofStirrup, Diameter)
 Return "somb", "len", "sos", "dia"
#Read the files#
Function (s* SmartContract) creat ReinforcementCage Cage (APIstub shim
ChaincodeStubInterface, args [ ] string) sc.Response
# Define constraints #
Somb_constraint_upper := 10
Len_ constraint_upper := 100
Sos_ constraint_upper := 20
Dia_ constraint_upper := 10
# SmartContract Result#
If somb <= Somb_constraint_upper
   &&len <= Len_constraint_upper
   &&sos <= Sos_constraint_upper
   &&dia <= Dia_constraint_upper
 Else
    Return shim . Error ("Invalid Reinforcement Cage Info")
Return shim . success(nil)
```

Fig. 8 Pseudocode of the chaincode for quality compliance checking of reinforcing cage.

supervisor on the client, the peer of owners check the information stored in the pre-block "Block $n + 1$", such as the digital signatures of the contractor and the supervisor, the format of the initial construction quality information, and so on. The checking result is recorded in the blockchain system named "Block $n + 2$". If the information passes, then the quality of the inspection batch is qualified. The compliance checking process is recorded in the blockchain system.

With the construction process, the construction quality information of each inspection batch is stored in the consortium blockchain system based on the consensus process. Then, supported by the smart contract, the construction quality compliance checking can be automated and achieved in the blockchain system, which aims to judge whether the project meets the requirements of quality regulations. Therefore, construction quality management can be controlled down to the basic unit referred to as inspection batch, solving the subjectivity in the compliance checking. Additionally, all operations are immutable and traceable in the blockchain system, which helps reduce unruly behaviors (e.g., cutting corners) and enhance mutual trust in the collaboration.

5 Visualization of a consortium blockchain network

For demonstrating the feasibility of blockchain technology in construction quality information management, we deployed the following development environment for the prototype blockchain system. In this study, Linux version 5.0.0-32-generic (buildd@lgw01-amd64-015) (GCC version 7.4.0 (Ubuntu 7.4.0-1ubuntu1~18.04.1)) with two Intel® Core™ i5-8250U CPU @ 1.60GHz processors, and 8 GB 2133MHz LPDDR3 memory was used. Additionally, the Docker engine (version 19.03.2) was adopted for building the environment for managing chaincode, and Docker-Compose (version 1.13.0) was adopted for creating isolated networks and configuring docker containers. Hyperledger Fabric (version 1.4) was used to develop our prototype blockchain system for managing construction quality information. The Hyperledger Explorer was adopted to visualize the consortium blockchain network in the prototype system. Hyperledger Explorer allows internal browsing of ledger items created by the members on the chain and can also monitor and query the blockchain network, such as get network and chaincode state, view blocks and transactions, filter blocks by conditions, and get real-time notifications of a new block.

Based on the Hyperledger Explorer, a simple blockchain system is visualized in which construction quality information would be transformed into transactions and then stored in the block through the consensus process. Figure 9(a) shows the details of Block 6, such as transaction number, block hash, data hash, and prehash. Figure 9(b) shows the transaction details in this block. Therefore, the blockchain system can achieve transparent and traceable information management. The quality accountability would be quick because the immutable quality information can be accessed by any participants on the chain at any time by proposing the query transaction. In this case, various participants can really trust one another, thus improving the efficiency and quality performance of the construction process.

6 Discussion

The construction industry is ranked as the second-lowest sector in adopting information technology (Agarwal et al., 2016). Blockchain can provide a ripe environment for the impending digital disruption in the construction industry by providing immutable, traceable, and transparent information records. However, a few challenges hinder the application of blockchain in the construction industry.

First, the implementation of the consortium blockchain system in the construction industry requires different participants to reach an agreement. However, the blockchain is still a quite new concept in the construction industry compared with other industries, such as finance and logistics. Understanding how to apply blockchain technology for a more effective and transparent business model may be a major obstacle for stakeholders (Penzes, 2018). The lack of understanding may prevent participants from adopting emerging innovation. Construction companies may refuse to distribute ledger access to all stakeholders considering they have maintained their business ledger private for decades (Wang et al., 2017). Additionally, the initial cost for developing the blockchain system is incurred at the primary application stage.

Second, the technical challenges limit the application of blockchain technology, including interoperability, throughput, and latency (Swan, 2015). Currently, the size and format of the data are limited to be uploaded to the blockchain. Blockchain is a distributed ledger, and the data are stored by each peer. Some valuable large files (e.g., video data and BIM models) can affect the performance of the blockchain. For example, the data volume of complete BIM models containing the geometric information is a burden for the performance of a blockchain, which involves numerous peers. Moreover, transactions cannot be approved until pre-defined stakeholders in the consortium blockchain system reach a consensus. However, the consensus increases the processing time of each operation. Nevertheless, many of these technical challenges are expected to be solved as new versions of blockchains are released.

Third, the policy environment of blockchain has not been well established, including the related regulations, laws, policies, and standards (Li et al., 2019). How to develop a regulatory environment to promote blockchain's adoption and integration with other digital technologies remains a challenge. Moreover, data privacy should be considered for blockchain-based applications that promote information sharing to avoid violation of privacy regulations.

These challenges can be solved as the technology further advances. The characteristics of blockchain make it the next disruptive technology that will propel the construction industry right into the middle of the Fourth Industrial Revolution (Kinnaird and Geipel, 2017). This research explores the potential application of blockchain technology in construction quality management, intending to improve information sharing and enhance mutual trust in the construction quality management. However, owing to its preliminary and exploratory nature, the research has several limitations that need to be explored in the future.

First, we proposed a blockchain-based conceptual framework for construction quality information in which

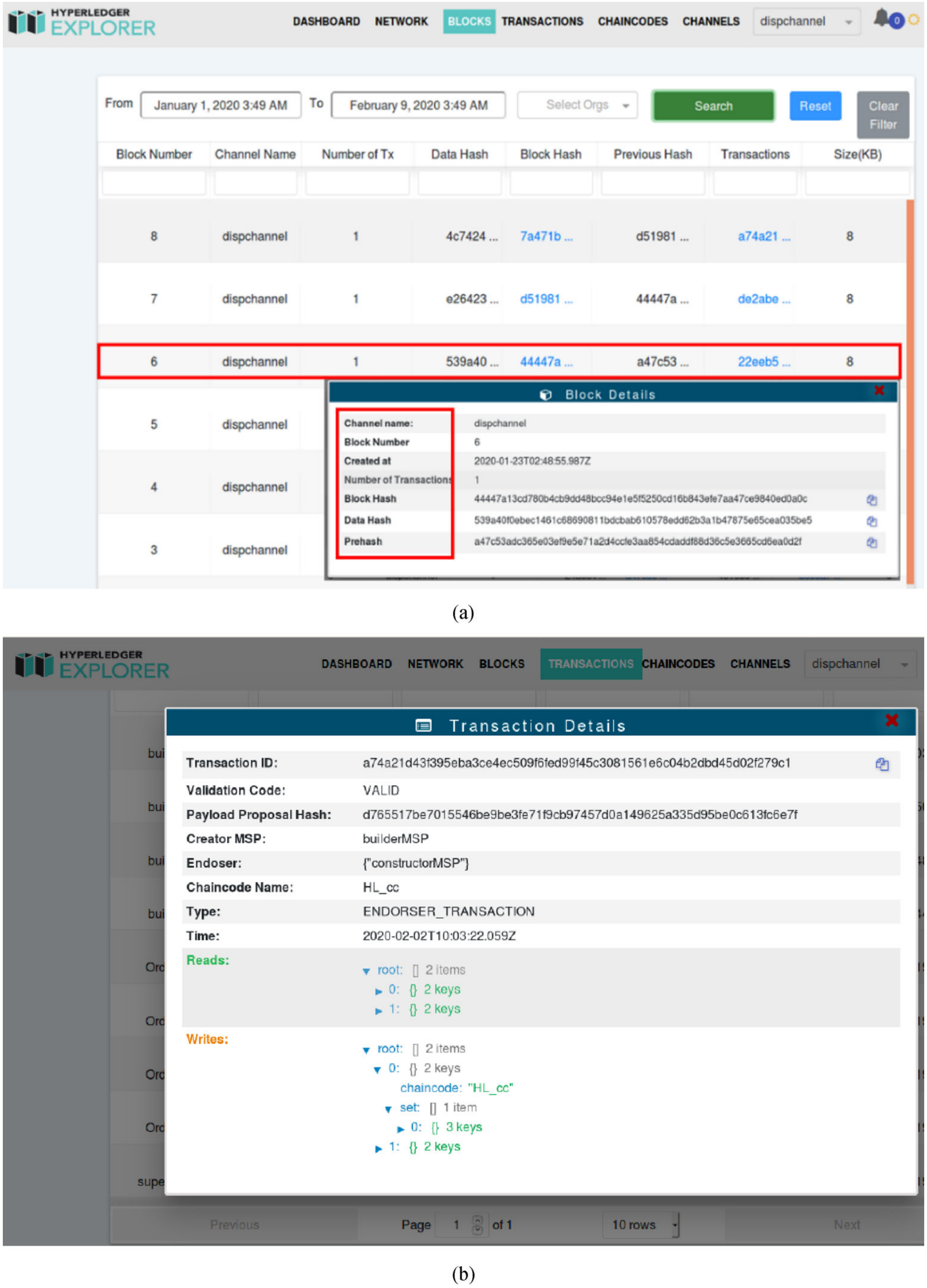

Fig. 9 Screenshots of information of the (a) blocks and (b) transactions in the consortium blockchain network based on Hyperledger Explorer.

BIM and IoT are involved. Rather than discuss how to solve the problems in combining these three technologies, the true aim of this paper is to explore the potentials of blockchain technology in construction quality information management considering that blockchain is a relatively new concept in the construction industry. The details of the integration process can be studied in future research, for example, the complex processes of consensus and scattering data in different blocks will affect the BIM application's performance to read and parse the on-chain data and increase time consumption.

Second, the proposed blockchain-based framework has not been validated in practical construction projects largely because the environment for applying blockchain has not yet been formed in the construction industry due to lack of understanding on the blockchain, implementation cost, technical challenges, and so on. Thus, a simple blockchain prototype system is developed, while the blockchain for construction quality management probably involves additional institutions in real environments. In the future, additional evidence from a practical application is needed for confirmation. Moreover, a comparative analysis between the blockchain and traditional information systems or tools can be performed in future research to verify the effectiveness of blockchain technology based on field data in practical construction projects.

7 Conclusions

Mutual trust can improve efficacy and quality performance of construction, which depends on immutable and traceable information records and real-time information sharing between various construction participants. With traditional information management systems, obtaining stakeholder trust is difficult due to information asymmetry.

Blockchain, as a disruptive technology, has the potential to improve mutual trust in the distributed cooperation environment. It can be used as a business tool, not merely a technological innovation, which can facilitate a paradigm shift in the industry toward effectiveness, accountability, and transparency (Penzes, 2018). In terms of construction quality management, blockchain can enable different organizations of a project to achieve consistent, secure, and decentralized construction quality information management, which is the basis of mutual trust.

This study fills the research gap for the blockchain network in the domain of construction quality management. A blockchain-based framework is proposed for managing construction quality information in an immutable, traceable, and transparent way. This study designs a consortium blockchain network for construction quality management in which the participants' information permissions and lifecycle are presented. Based on the HLF platform, the consensus process of the consortium blockchain is introduced for recording information. Additionally, supported by smart contracts, the automated compliance checking process is discussed, which can improve efficiency and avoid subjectivity in construction quality acceptance. Lastly, a prototype system of the consortium blockchain is developed, and the Hyperledger Explorer is used to visualize this network to show its feasibility on information management.

The proposed blockchain-based framework can facilitate construction quality management by providing distributed, encrypted, and secure information records and supporting automated compliance checking based on smart contracts. Currently, the research on blockchain technology in the construction industry is still in the exploration stage, and most of the previous studies belong to the conceptual discussion. This study may be a beneficial attempt for blockchain research in construction quality management.

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