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Construction quality information management with blockchains

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ABSTRACT

The information generated from a nonconformance can be used to determine the party responsible for ensuring that quality standards are assured. However, in the construction industry, the absence of a uniform and transparent system for managing quality information undermines the assurance process and may lead to disputes among stakeholders. In addressing this issue, we develop a blockchain-based framework for managing quality information, referred to as "Product Organization Process (POP) qualityChain". A Hyperledger-Fabric-based architecture and a series of blockchain solutions (e.g., a POP-model-based quality information structure, a consensus mechanism, smart contracts for processing quality information, authorization sequences, and execution processes) are covered. Finally, we build a prototype system and use a case study to validate our framework. Results show that the proposed framework can decentralize the management of quality information, thereby achieving consistent and secure quality information management. Future work could seek more evidence from practice to further validate our framework.

1. Introduction

Nonconformances (NCRs) are product of poor quality and are common occurrence in construction projects. At times, determining who is primarily responsible for them can be an arduous task. In many instances, NCRs are not reported or are inaccurately documented, which makes determining the person or party responsible for ensuring that work adheres to specified requirements difficult [1]. Being able to accurately capture NCRs improves the ability to trace their history and provides an opportunity for construction organizations to learn from their occurrence. Furthermore, having a robust system to trace NCRs enables those responsible for their rectification to be held accountable. However, in the construction industry, a system within a project supply chain that can readily capture quality data and ensure its security is lacking [2–4]. Despite the efforts of contractors to build systems for managing quality information, such a centralized system governed by contractors may still face difficulties in tracing NCRs. A lack of confidence is observed in the authenticity and integrity of the documented data among project stakeholders. Data are maintained exclusively by the contractor; thus, the contractor has a motive and an opportunity to modify the data to exonerate itself when an NCR occurs. A uniform, secure, and transparent system that is co-managed by stakeholders for managing quality information is an urgent need; obviously, a centralized system is not an adaptable solution.

Blockchain is a disruptive technology that can guarantee data security. In simple terms, a blockchain is a decentralized database that chronologically and securely records transactions (e.g., financial and the transfer of value) [5]. Data are written through a complex distributed consensus process without relying on any central administrator; thus, the uploaded data must be validated by all participant nodes. These nodes also maintain copies of the data, rendering it impossible for anyone to have control over the data. Value in this instance may be a service, product, or an approval that emanates form of a smart contract [6]. The potential use of blockchains includes (1) recording value exchanges [7], (2) administering smart contracts [8], and (3) certification of proof of existence (e.g., digital identification [9]).

On this basis, we present a novel blockchain-based framework to provide organizations the ability to capture their quality management information and therefore improve their capacity to learn and business performance. This framework for managing quality information is called the "Product Organization Process (POP) qualityChain." The on-chain quality information is structured by a POP model which defines the relationships among an organization, its product, and process dimension. We then develop a Hyperledger-Fabric-based architecture and a series of blockchain solutions (e.g., a consensus mechanism, smart contracts for processing quality information, authorization sequences,

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and execution processes) to support the management of quality information. Our proposed blockchain framework is implemented using a case study and its performance reported upon.

2. Related research

Opportunism and bounded rationality are common in construction projects that are obtained using traditional contracting methods [10]. Projects are ephemeral and organizations involved with their delivery tended to have divergent goals and objectives. As a consequence, the development and maintenance of trust in projects has been a constant challenge [11,12]. Since the publication of the Latham Report, considerable advances have been made to build trust in project teams in construction through the use of partnering and alliance contracting, to name a few [13,14]. Collaboration is a widely accepted key ingredient to project success, especially for ensuring project quality [10].

A project quality management information system can provide the basis for recording and communicating management information in a timely manner and can thus be used to improve decision making [15–17]. However, such project-based systems tend not to be transparent, and a predisposition often exists for contractors to possess a biased outlook when determining the responsibility for an NCR. With the advent of building information modeling (BIM), the ability to ensure the transparency of information between parties is enhanced, particularly when integrated with a blockchain-enabled smart contract. The decentralized and trustless nature of blockchain technology provides a robust mechanism for improving the way in which quality information in construction is managed. We now provide a brief review of the blockchain literature. (For an in-depth exposition on the nature of blockchain technology, refer to the following works: Weber et al. [18], Ølnes et al. [19], and Li et al. [20]).

Blockchain is used in various areas, such as accounting [21,22], supply chain management [15,23], transportation [24], and assets management [25]. Table 1 presents examples of where blockchain technology has been applied. Within construction, blockchain technology is still at its infancy, and to the best of our knowledge, no empirical studies have yet demonstrated its benefits. Studies that have been undertaken have tended to be based on reviews and the developing conceptual models for application [20,26–29].

3. Blockchain and smart contract

Briefly, a blockchain is a distributed ledger that combines asymmetric encryption technology with hash functions to form peer-to-peer (P2P) networks. Here, Merkle trees, consensus algorithms, and other technologies enable multiple nodes to collectively maintain a shareable and tamper-proof ledger and promote collaboration within a decentralized system. Fig. 1 shows the data structure of the blockchain.

A block consists of two parts, namely, the header and the body. In the header, three hash values are included. A hash value is a fixed-length output returned by inputting data of arbitrary length into the hash function. Hash functions are input-sensitive; even if a slight difference exists between the two inputs, the outputs are distinctly different. A hash value can serve as a fingerprint or digest for the data. The first hash value in the header of a block is the digital digest of its parent block, and the second one is the digital digest of its own content containing the first hash value (e.g., Block_n Hash and Block_{n+1} Hash of Block_{n+1}). The mechanism enables the blocks to structure a chain. Small perturbations in a block can lead to inconsistency between a new parent block hash and the old parent block hash of the next block due to the sensitivity of the hash function to inputs; this phenomenon further affects the next block, and so on. The hash value plays a crucial role in ensuring the integrity of the ledger. Merkle root—the third hash value in the header of a block—is a final value obtained by multiple hash operations—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 have been tampered with. The body of a block covers all transaction records during the block time.

Different types of blockchain possess varying level of access. Three types of blockchain have been developed:

1. Public blockchain: This form of blockchain is completely decentralized. Everyone can join the network at any time, act as a peer, and maintain a complete ledger. Furthermore, users, even if without the willingness to store a ledger, can also access (cannot modify and delete) the data, submit a transaction, and obtain consensus from the public network through the client or browser without restrictions. Notable examples of public blockchains are Bitcoin and Ethereum.
2. Consortium blockchain: This type can be categorized as a multicenter system. In most cases, peers of the network are limited to an alliance of multiple participants or enterprises. Before the network is established, the members of the alliance determine through negotiation that part or all of the participants separately hold and maintain the ledger. On this chain, read–write access permission can be controlled; thus, data can be made available only to authorized participants.
3. Private blockchain: Typically, this type of blockchain is utilized for internal business alignment in a large organization, such as a transnational enterprise. The data are stored in one or several data centers of the organization. Access to this blockchain is restricted within the organization, that is, only authorized organization members can access the data. Notably, a private blockchain supports an organization to establish a secure, traceable data platform to

Table 1
Examples of blockchain applications.

Research field	Application	Reference
Health and medical treatment	A framework based on blockchain, particle swarm optimization, and advanced encryption standard is proposed to the protect biometric data of patients (e.g., finger vein biometric data).	[30]
	A blockchain-based Internet of Things (IoT) system is used to share health information collected by sensors and wearable devices in response to medical big data needs while ensuring privacy.	[31]
Electricity	The proposed consortium blockchain solves the low data aggregation efficiency in a centralized power grid system, and the smart contracts help give users accurate feedback.	[32]
	Blockchain networks constructed by distributed measurements enhance the power grid's ability to resist network attacks, and the effectiveness of the framework is verified based on simulation experiments.	[33]
Food and drug	The asymmetric information of market is eliminated through the consortium blockchain, and on this basis, a sustainable and credible trading environment is established to ensure the interests of small-to-medium-sized enterprises in the agricultural sector.	[34]
	A decentralized application (DApp) based on smart contracts is developed to monitor the supply chain environment of drugs to combat drug counterfeiting, and recursive verification for every transaction is allowed on the DApp.	[35]
Environment	An emissions trading policy and implementation platform based on the Hyperledger Fabric is design and established. The incentive mechanism can curb pollution efficiently.	[36]
Education	Credit and degree system with smart contracts certify credits and award degrees in a trusting and transparent manner, which reduces the bureaucracy involved in verifying official documents.	[37]

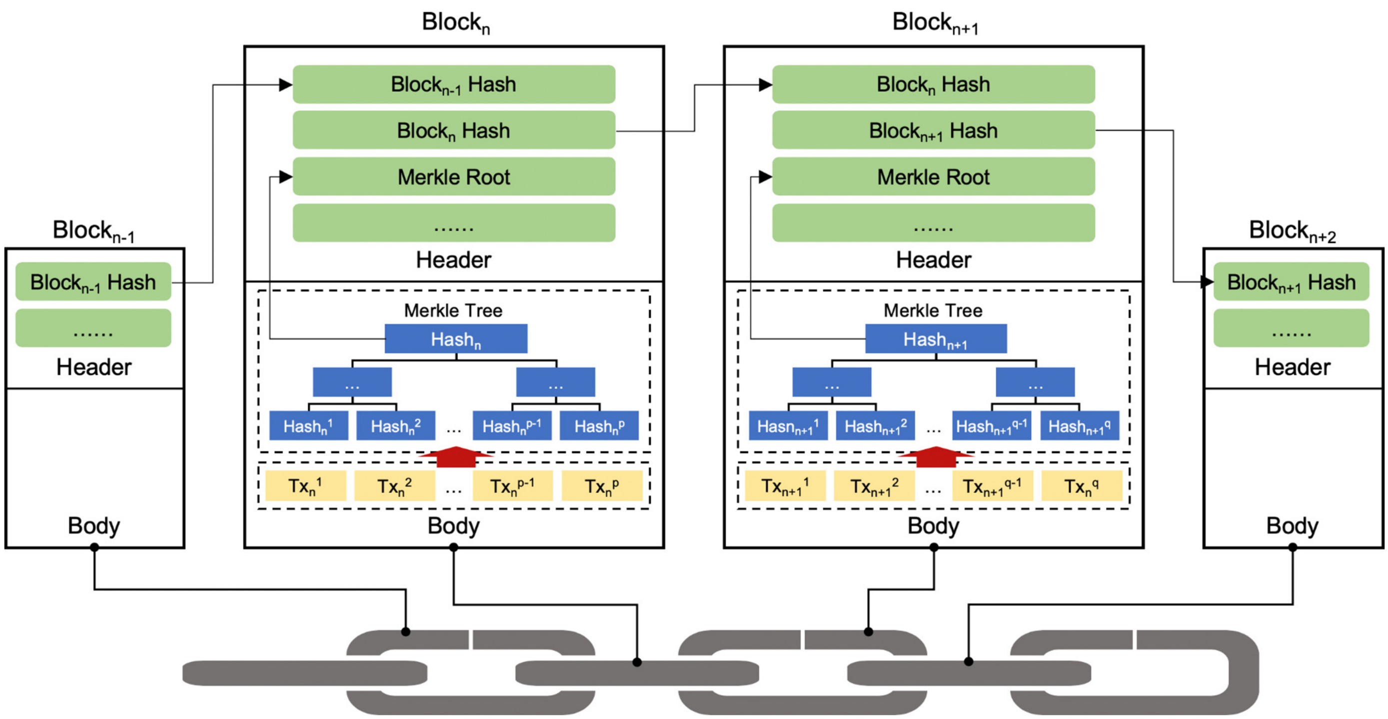

Fig. 1. Data structure of a blockchain [5].

coordinate different internal departments.

Blockchain can support the use of smart contracts [38]. Smart contracts are programmatic objects that can self-execute terms of a contract. By coding the terms, the agreement is transparently implemented without central authority. A smart contract contains the trigger conditions for responses and actions that need to be performed after the trigger [39], as shown in Fig. 2. Once deployed, it can continuously monitor data changes on the blockchain or external data source and automatically execute when the conditions are met without complicated steps in the traditional business process. Supported by some programming languages with excellent programable performance, smart contracts can handle complex business scenarios, such as the IoT [40] and banking [41].

The combination of the tamper-proof recording capacities of blockchains and the automated information processing capacities of smart contracts enables an information system to remain neutral across multiple parties, regardless of whether they trust one another. Consequently, it can benefit the management of quality information in the construction industry from the following aspects:

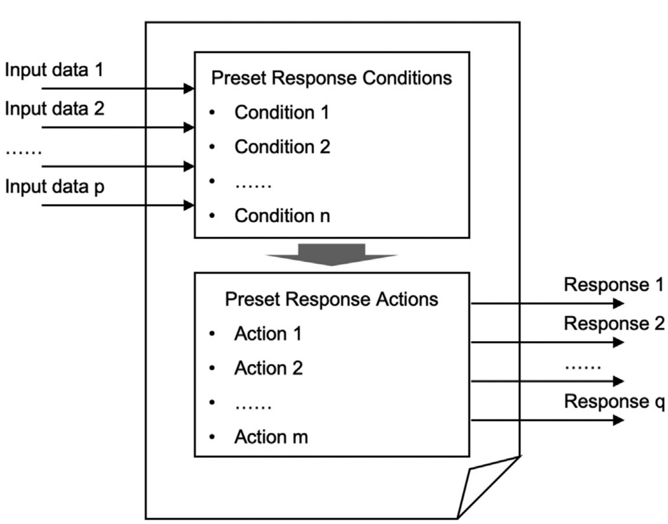

Fig. 2. Schematic of smart contract.

- The quality information documented on the blockchain is completely transparent to the project stakeholders because of the consistency of ledgers. As a result, information sharing can be unimpeded, and risks can be captured timely from the quality information.
- Given its tamper-proof capability, the on-chain quality information is immutable and traceable; by contrast, during the decade-long operation of construction products, the information in the traditional centralized system has the risk of being distorted. Such distortion may be caused by various possibilities, such as malicious tampering or file corruption.
- Smart contracts can standardize the management process of quality information and avoid certain violations of processing quality information, such as unauthorized signature.

4. Blockchain framework for quality information management

In this section, we develop a blockchain-based framework, POPqualityChain, which can be used to manage quality information and ensure its trustworthiness. The conceptual scenario is presented in Fig. 3. POPqualityChain adopts a consortium blockchain framework, and it is established and maintained by organizations involved in the project supply chain (e.g., owners and contractors) within a region. Through the application clients, the quality information captured in the construction site can be uploaded to the POPqualityChain for documentation. Moreover, the technical characteristics of our blockchain ensure that it cannot be tampered with and that all quality information is traceable.

4.1. POPqualityChain-based for quality information management

POPqualityChain-based quality information management is an

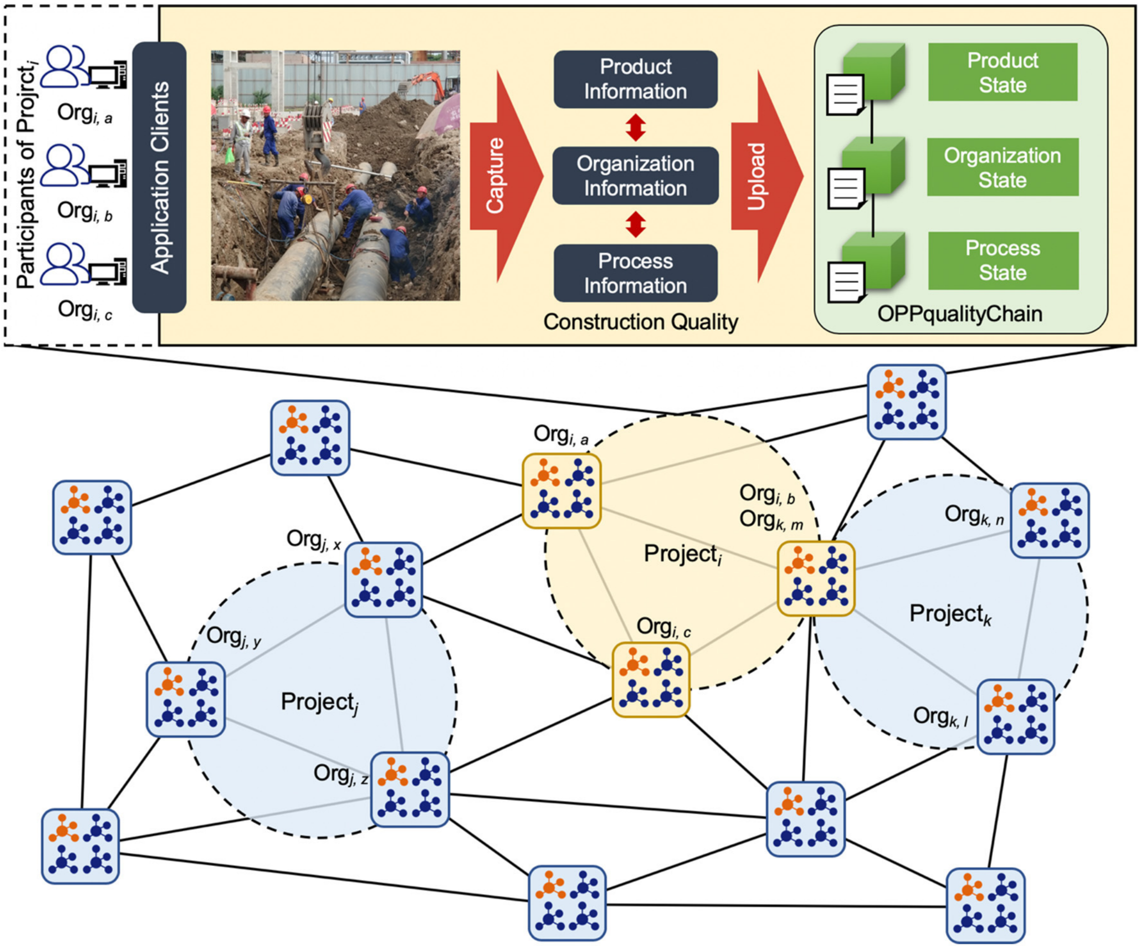

Fig. 3. Conceptual scenario of POPqualityChain.

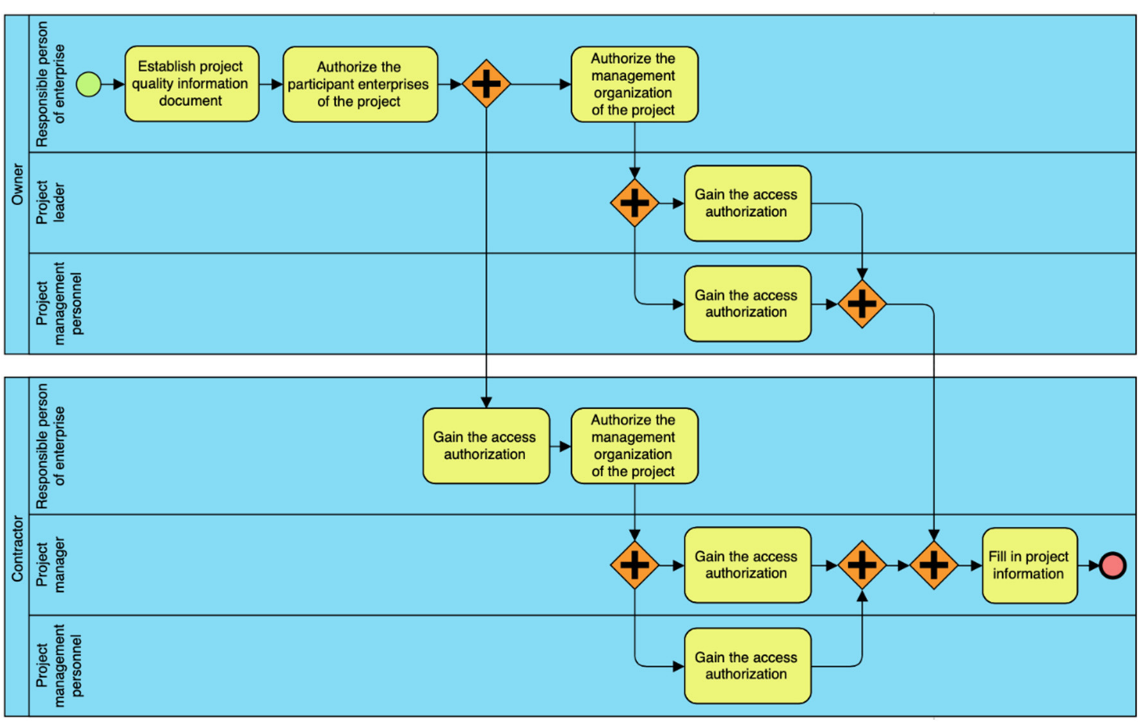

Fig. 4. Alliance process between an owner and a contractor.

online collaborative process among project participants. After signing the project contract, a conventional project-based alliance is formed. Subsequently, the participants (e.g., owner, contractor, subcontractors, and suppliers) jointly participate in the POPqualityChain after reaching an agreement. Fig. 4 illustrates the process of recording and processing quality information between an owner and contractor after their participation in the POPqualityChain. The process is commenced by the asset owner, for example, by creating a quality information document on the POPqualityChain. Typically, an asset owner will have a project portfolio in place. Thus, the department responsible for administrating them will be required to ensure that the POPqualityChain, in collaboration with contractors, is implemented in all projects. Once authorizations have been enacted, the POPqualityChain is ready to be used.

We now present a brief example of how the POPqualityChain works. As the output of work breakdown structure technique, inspection lots are the smallest indivisible cells according to China's unified standard for constructional quality acceptance. The necessary condition for subproject acceptance is that its inspection lots are all qualified. The quality acceptance records of inspection lots are also an important part of project documents. Fig. 5 presents the recording process of inspection and acceptance of a cast-in-situ bored pile inspection lot. The information is recorded into the POPqualityChain. The contractor completes a template and provides all relevant information. The data are collected by the quality inspector and inputted into the POPqualityChain. The supervising engineer checks the integrity, consistency, and accuracy of the quality data on the form, accepts the work result, and signs it off. Notably, the contractor and the supervising engineer must require to sign-off for the work. If the acceptance is qualified, then the project moves to the next task; otherwise, the contractor needs to rectify the work, and the entire process is repeated.

4.2. POPqualityChain framework

4.2.1. POP-model-based quality information structure

Chen and Luo [42] developed a POP model for BIM-based quality management in construction. The POP model can interrelate the product dimension, organization dimension and process dimension of construction quality information [43]. As a result, it can automatically identify the location of a defective component within a model. The party responsible for the defect can be determined and issue an NCR.

In this study, the POP model established in the previous work [42] was adopted for structuring the on-chain quality information. Fig. 6 presents part of POP-quality-based information model on the basis of Integration DEFinition for information modeling (IDEF1X) standard. In this manner, when any quality problem occurs during the operation stage of the construction product, the structural and tamper-proof characteristics of the construction quality information on the POPqualityChain are committed to liability cognizance. Moreover, the horizontal comparisons for the timely identification of potential quality defects in other projects involving the responsible person and enterprise can be supported.

4.2.2. Architecture of POPqualityChain-based system

Hyperledger Fabric, an open-source blockchain infrastructure project developed by IBM, is currently one of the most mature distributed ledger platforms [44]. It is oriented to cross-industrial application and has been applied to a large number of commercial projects. Rather than an open, anonymous and unrestrained blockchain system, such as Ethereum, Hyperledger Fabric has following advantages to enable it to fulfill more business requirements [45,46]:

- Permissioned architecture: The optional Membership Service Provider (MSP) module allows organizations to issue digital certificates for managing and validating the identity of members.
- Modular components: Hyperledger Fabric provides pluggable function module components, such as member management and consensus algorithms, which can simplify the difficulty and cost for development.
- High scalability: Scalability is used to describe the number of participants that the network can serve. The number of participant nodes is unlimited in the Hyperledger Fabric network and does not affect performance, such as throughput and latency.
- Support for smart contracts: Several Turing-complete programming languages (e.g., Go and Java) are supported for coding smart contracts to flexibly implement business requirements.

Thus, we select the Hyperledger Fabric architecture to develop our framework. Fig. 7 presents the POPqualityChain architecture, which consists of four layers, namely, (1) data, (2) network, (3) consensus, and (4) application.

The data layer contains quality information with a block as the basic storage cell within the POP model's information structure. The chain's structure is formed when the hash function maps the contents of a block to a non-invertible hash value to the fixed length of the next block. Notably, only smart contracts, predefined based on the quality management system, can process the data directly on the chain. By doing so, the quality information is assured to be processed consistently rather than arbitrarily. The quality information is written by invoking the unified templates designed based on the POP model, such that the information scattered in the blocks can be parsed by the upper quality application layer.

The network layer determines the members of the POPqualityChain and forms a P2P network without a central server. The asymmetric cryptographic technique is used to confirm the identity of each node and clarify the ascription of responsibility for processing on-chain

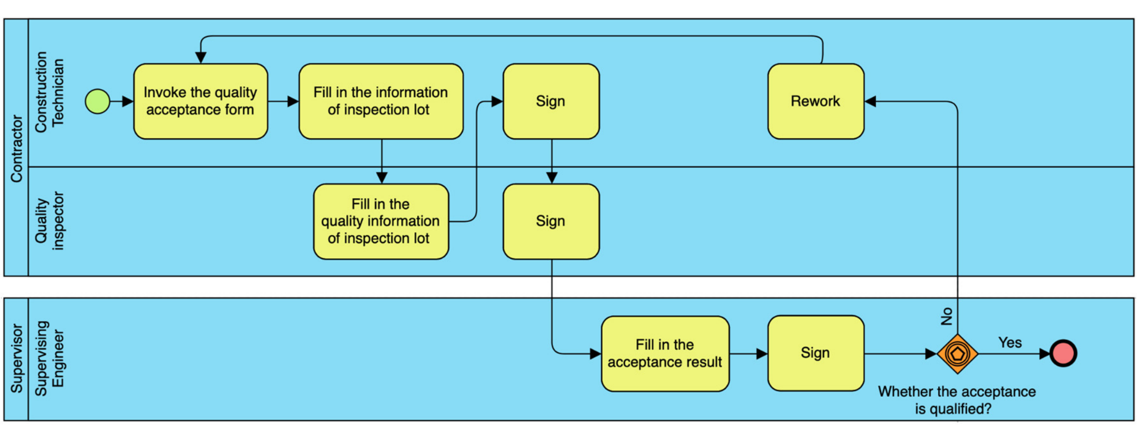

Fig. 5. Recording process of a cast-in-situ bored pile inspection lot.

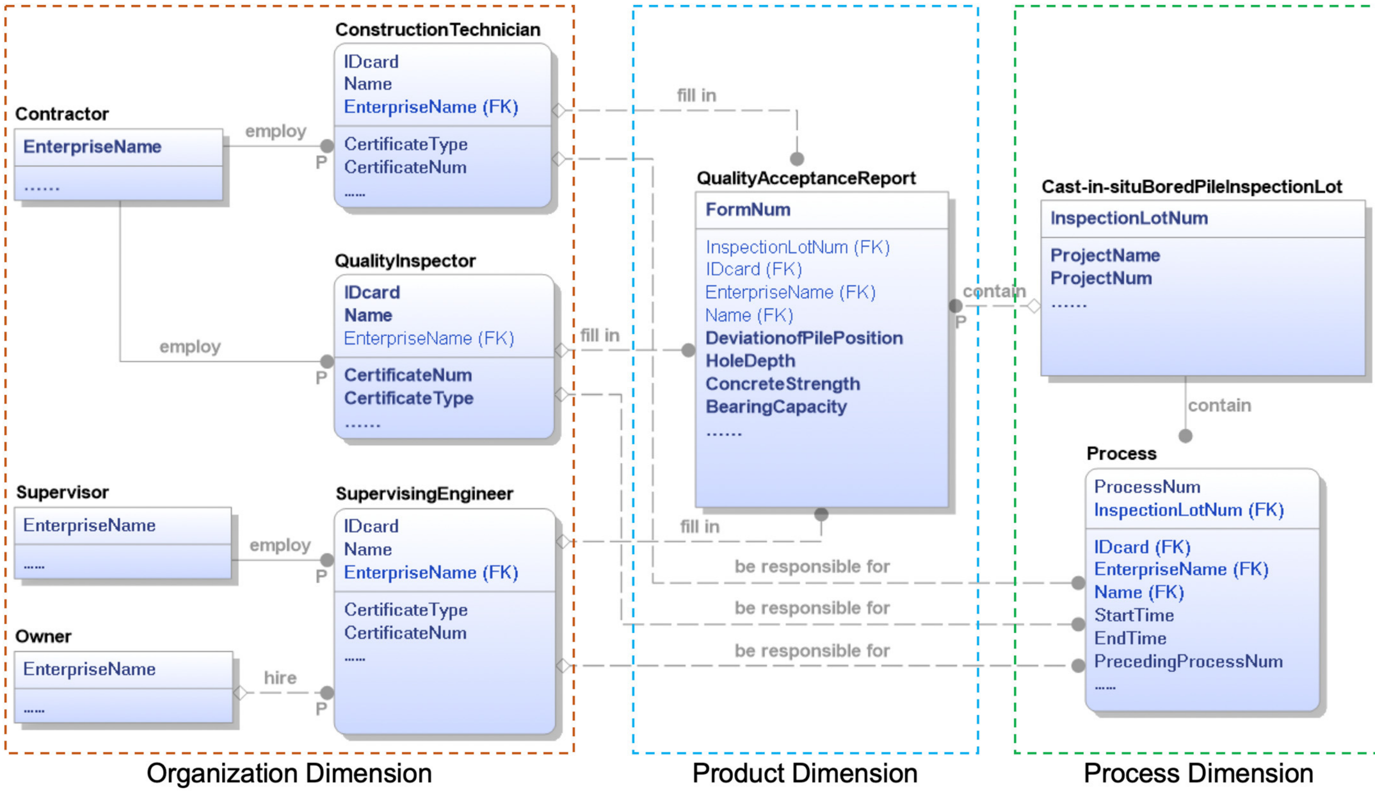

Fig. 6. Part of POP-model-based quality information structure [42].

information. Different from a public blockchain, which anyone can access without limit, our POPqualityChain is based on a Hyperledger Fabric that can authorize multiple users and restrict access to information. In our P2P network, the three main peer roles are (1) ordering, (2) endorsing, and (3) general, which correspond to the red, orange, and blue nodes in Fig. 7, respectively.

The consensus layer focuses on reaching a consensus between nodes. That is, how to add the next block to the current chain in a trustless distributed computing environment. As the parties have agreed to jointly record information in POPqualityChain, this is an explicit incentive to ensure that the computational costs associated with the exchange for rewards is not required. In facilitating this consensus process, we use an Apache Kafta® distributed streaming platform. The application layer shields the end user from the complexity of the underlying quality information management logic and provides a user-friendly interface to record, conduct inquiries, and authorize access to information.

4.2.3. *Consensus mechanism in the POPqualityChain network*

The Hyperledger Fabric Kafka consensus module is selected due to its advantage of low latency, high throughput, and high concurrency and its ability to synchronically process a large quantity of information [47]. The algorithm comprises three steps, that is, (1) transaction proposal endorsement by endorsing peers, (2) transaction ordering by ordering peers, and (3) transaction verification by peers.

Numerous enterprises participate in the POPqualityChain network, and each enterprise consists of an endorsing peer and several general peers. The endorsing peer is served by the enterprise server, and the personnel involved in quality management are general peers. Each peer can submit transactions to record and process information within their predefined authorization. Furthermore, the enterprise's endorsing peer is responsible for verifying transactions by simulating execution and signing and holding the ledger backup for quality information. In addition, the selection of endorsing peers for a transaction to process quality information is based on a case-by-case approach and is predefined by the endorsing policy of smart contract instance. Ordering is a crucial step in the consensus processes. The ordering peers collect and order all transactions within a block time, package them into a block, and broadcast the block to each peer for updating their own ledger backups. In this manner, the inconsistent transaction orders received by different endorsing peers caused by network performance differences can be shielded, such that the equal block hash can be gained in the POPqualityChain backups of different endorsing peers. In comparison with proof-of-work consensus where miners gain the accounting rights through computational competition, several peers can be selected to provide ordering service on the POPqualityChain; for example, off-chain negotiation or on-chain voting among the participants on the chain is a feasible method. Finally, the double-spending verification for the new block is implemented by each peer to avoid the quality information being repeatedly recorded.

4.2.4. *Smart contracts for processing quality information*

Smart contracts are also referred to as *chaincodes* in the Hyperledger Fabric architecture. They enable a blockchain to implement complex functions and business logic, not simply for storing data. Smart contracts stipulate the rights and responsibilities of all parties in a project alliance. They are also the trusted distributed applications deployed on the blockchain. Once deployed, the unique addresses on the chain are allocated to the smart contracts.

When the data inputted to blockchain encounter a trigger condition of a smart contract, the predefined actions in the smart contract are automatically and independently executed. In our framework, smart contracts are intermediaries for participants to interact with the blockchain. For example, a contractor may submit a form indicating a cast-in-situ bored pile conforms, and a supervising engineer accepts this recommendation by signing the work off. Then, in accordance with the predefined actions, smart contracts add the quality information of the cast-in-situ bored pile to the POPqualityChain by submitting

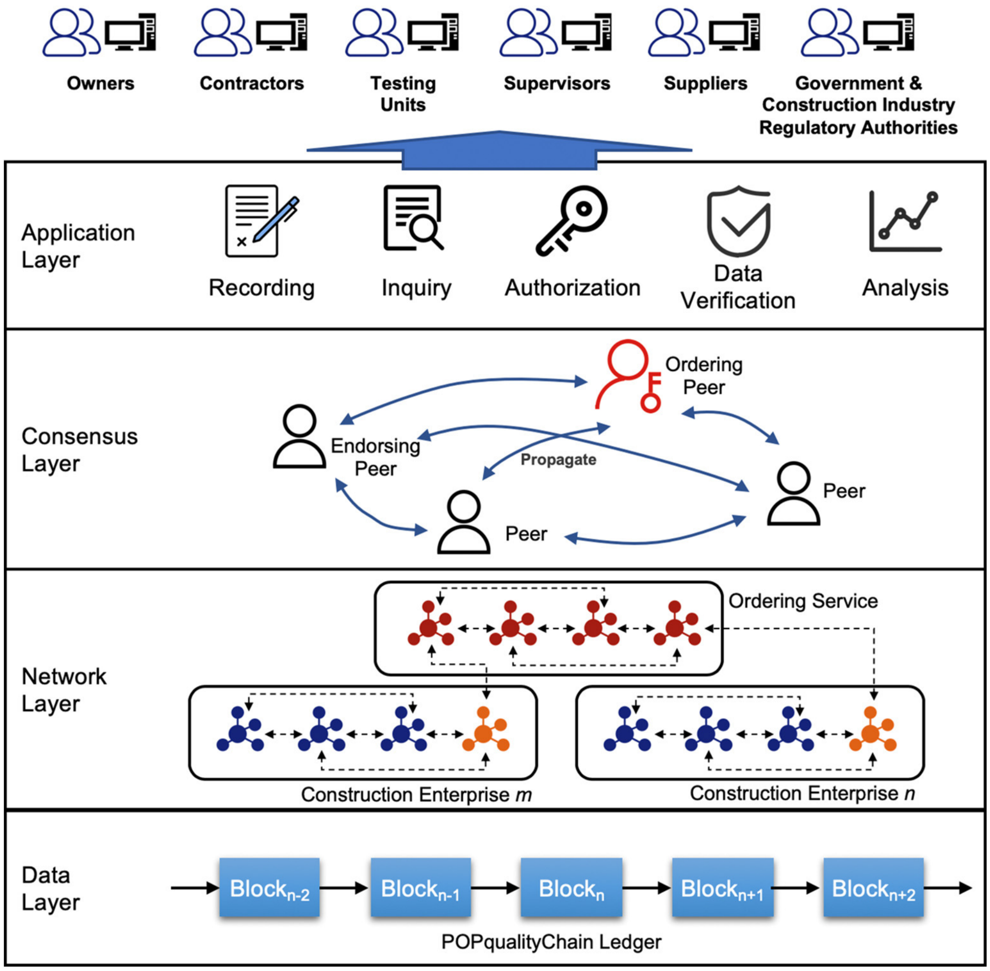

Fig. 7. POPqualityChain-based quality information system architecture.

transactions.

Those involved in the blockchain network can only process information within the scope of their obtained permissions. When they process quality information at the visual interface of the POPqualityChain, the smart contracts deployed on the chain monitor input parameters and provide feedback on different types of request, such as queries. The transaction is then adhered to the block, whereas the state in the ledger is updated and returned to the user. This process is presented in Fig. 8. In a smart contract, the intermediate interaction with quality information on the chain is predefined with the transactions, and the events are defined to interact with the participants on the chain. Table 2 shows the parts of transaction and event definitions for quality information processing.

Smart contracts define operations through transaction process function programming. Fig. 9 presents an example of a "Create Quality Information Form" transaction process function for generating the acceptance record of a cast-in-situ bored pile quality.

4.2.5. Authorization sequence on the POPqualityChain

As a quality information ledger of construction projects within a region, the POPqualityChain needs the authorization function according to the following facts. First, in our country, the quality information of all construction projects is required to be disclosed to the government and construction industry regulatory authorities, which facilitate the implementation of regulation. Second, the quality information of a construction project cannot be captured by persons unrelated to the project because of the confidential corporate data involved. Third, the responsibility of each step of a construction project should be clearly defined, such that a certain person can be held accountable for an NCR. On the basis of the above considerations, a typical but not unique authorization sequence in the POPqualityChain network is introduced here.

Given the role of regulation, the government and construction industry regulatory authorities initially take precedence over the enterprises in the sequence. Then, owners, the initiators of the construction projects within the region served by the POPqualtiyChain, are on the second level. With regulatory approval, a dedicated on-chain quality information document of a construction project can be created by its owner. Under the owner's permission, the contractor and the supervisor obtain the third level of authority. Subsequently, whether professional contractors, labor subcontractors, and others are needed is determined on the basis of project complexity and the capabilities of the contractor. After obtaining the authorization from the contractor, they can participate in the project alliance. Beyond that, each unit also needs to authorize its own internal management team. Fig. 10 shows the abovementioned authorization sequence on the POPqualityChain.

MSP and Fabric CA modules are used to realize this authorization sequence in the proposed POPqualityChain framework. The MSP module enables the POPqualityChain to establish a credit certificate system and verify membership based on a public key infrastructure. The Fabric CA module supports the membership registration function and manages the member certificates (e.g., those associated with adding and revoking). After registering with the system, the enterprise or individual users can obtain an enrollment certificate (*E*-Cert), which includes the identity information, and a transaction certificate (T-Cert), which is used for signing transactions. According to the authorization

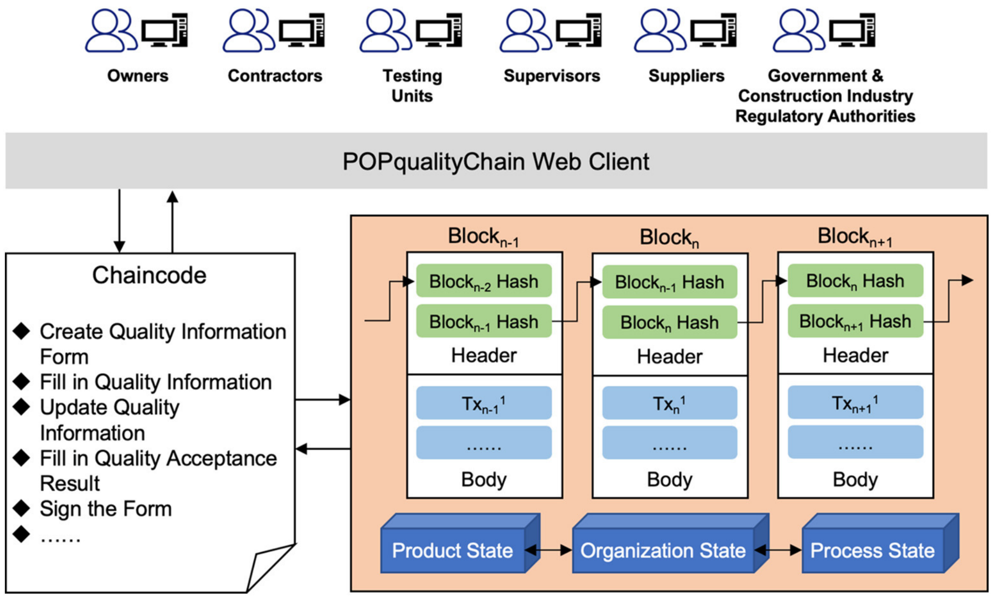

Fig. 8. Smart contract for processing quality information.

sequence on the POPqualityChain, the government and construction industry regulatory authorities hold the root certificate and play the root certificate authority role. Along the direction of the arrow in Fig. 10, the object at the end of the arrow acquires a next-level certificate.

4.2.6. Execution process on the POPqualityChain

Fig. 11 shows the execution process on the POPqualityChain. The process mainly includes two parts: (1) registration of POPqualityChain participants and (2) their processing for quality information.

As described in Section 4.2.5, the identity and affiliation of POPqualityChain participants must be strictly and clearly stated. Through the POPqualityChain web client, the participants can send a registration request to the Fabric CA module, and the certificates (including *E*-Cert and T-Cert) are then generated and fed back as responses.

After registration, the POPqualityChain participants can process information on the chain within the permitted limits. For example, in the case of the cast-in-situ bored pile, after its completion and before the acceptance, the contractor's quality inspector must submit quality information of the inspection lot to the POPqualityChain timely, including the bearing load capacity, perpendicularity, and hole depth. Through the web client, the POPqualityChain participants execute quality information processing transactions. In the above scenario, the quality inspector fills in the quality information on the corresponding quality acceptance form. The web client then sends a Fill in Quality Information transaction proposal defined with a smart contract to the POPqualityChain network. After the consensus process, the fresh quality information will be adhered to each POPqualityChain ledger backup. Specifically, after receiving the transaction proposal, the endorsing peers simulate the transaction execution, verify it, and sign the result of simulation. Until sufficient simulation results with signature are received, the client sends them to the ordering peers. A new block is generated with the ordering service and then broadcasted in the POPqualityChain network. Each peer performs a double-spending validation on the new block and transactions to avoid the quality information from being recorded repeatedly. Subsequently, the quality information of the cast-in-situ bored pile inspection lot is written in every POPqualityChain ledger backup and waits for the next step of acceptance. The web client will be notified when the transaction is accepted by the network.

5. Implementation of the POPqualityChain framework

We built the Construction Quality Integration System® (CQIS) to validate the proposed POPqualityChain framework. CQIS is a prototype system that aims to serve construction projects in Wuhan for managing quality information generated from acceptance in a secure, consistent, and reliable manner.

5.1. Prototype system

We used the following blockchain development environment to implement the proposed framework. 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(R) Core(TM) i5-8250U CPU @ 1.60 GHz processors and 8 GB 2133 MHz LPDDR3 memory was used to

Table 2
Part of transaction and event definitions for quality information processing.

Component	Type	Role
Create Quality Information Form	Transaction	Create a quality information form by the special responsible person
Fill in Quality Information	Transaction	Fill in the quality information within the scope of responsibility by the special responsible person
Update Quality Information	Transaction	Modify the quality information on the form by the special responsible person
Fill in Quality Acceptance Result	Transaction	Fill in the results of quality acceptance by the person responsible for quality acceptance
Sign the Form	Transaction	Sign the form by the responsible person
Create Quality Information Form Notification	Event	Notify each responsible person of the form that the form has been created
Fill in Quality Information Notification	Event	Notify each responsible person of the form that the quality information has been filled in
Update Quality Information Notification	Event	Notify each responsible person of the form that the quality information on the form has been modified
Fill in Quality Acceptance Result Notification	Event	Notify each responsible person of the form that the acceptance result has been given
Sign the Form Notification	Event	Notify each responsible person of the form that the form has been signed for

```
type SmartContract struct {
  }
    type Form struct {
        Form_Id          string         `json:"form_id"`
        Project_Name          string         `json:"project_name"`
        Unitproject_Name          string         `json:"Unitproject_name"`
        Subproject_Name          string         `json:"subproject_name"`
        Owner_Org          string         `json:"Owner_org"`
        Contractor_Org          string         `json:"supervisory_org"`
        Project_Manager          string         `json:"project_manager"`
        Check_Volume          string         `json:"checked_volume"`
        Check_Part          string         `json:"checked_part"`
        //Main items
        Hole_Depth          float64         `json:"hole_depth"`
        Hole_Depth_Result          string         `json:"hole_depth_result"`
        Mud_Weight          float64         `json:"mud_Weight"`
        Mud_Weight_Result          string         `json:"mud_weight_result"`
        Mud_elevation          float64         `json:"mud_elevation"`
        Mud_elevation_Result          string         `json:"mud_elevation_result"`
        End_Bearing_Pile          float64         `json:"end_bearing_pile"`
        End_Bearing_Pile_Result          string         `json:end_bearing_pile_result"`
        Friction_Pile          float64         `json:friction_pile"`
        Friction_Pile_Result          string         `json:friction_pile_result"`
        Underwater_Perfusion          float64         `json:underwater_perfusion"`
        Underwater_Perfusion_Result          string         `json:underwater_perfusion_result"`
        Dry_Construction          float64         `json:dry_construction"`
        Dry_Construction_Result          string         `json:dry_construction_Result"`
        Cage_Depth          float64         `json:cage_depth"`
        Cage_Depth_Result          string         `json:cage_depth_result"`
        Concrete_Filling_factor          float64         `json:concreate_filling_factor`
        Concrete_Filling_factor_Result          string         `json:concrete_filling_factor_result"`
        Pile_top_elevation          float64         `json:pile_top_elevation"`
        Pile_top_elevation_Result          string         `json:pile_top_elevation_result"`
    }
func (s *SmartContract) Init(APIstub shim.ChaincodeStubInterface) sc.Response {
        return shim.Success(nil)
    }

    func (s *SmartContract) Invoke(APIstub shim.ChaincodeStubInterface) sc.Response {
       function, args := APIstub.GetFunctionAndParameters()
       if function == "queryForm" {
           return s.queryForm(APIstub, args)
       } else if function == "createForm" {
           return s.createForm(APIstub, args)
       }
        return shim.Error("Invalid Smart Contract function name.")
   }
//query
    func (s *SmartContract) queryForm(APIstub shim.ChaincodeStubInterface, args []string) sc.Response {
       if len(args) != 1 {
            return shim.Error("Incorrect arguments. Expecting a key")
       }
        formAsBytes, _ := APIstub.GetState(args[0])
        return shim.Success(formAsBytes)
    }
```

Fig. 9. Example of transaction process function for creating a quality acceptance form of a cast-in-situ bored pile.

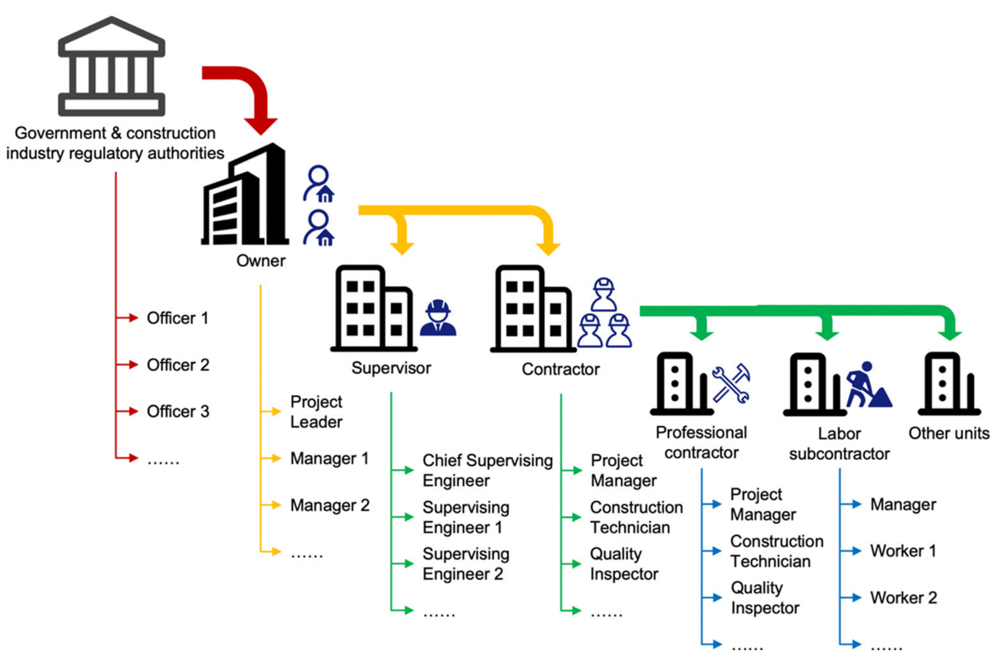

Fig. 10. Authorization sequence on the POPqualityChain.

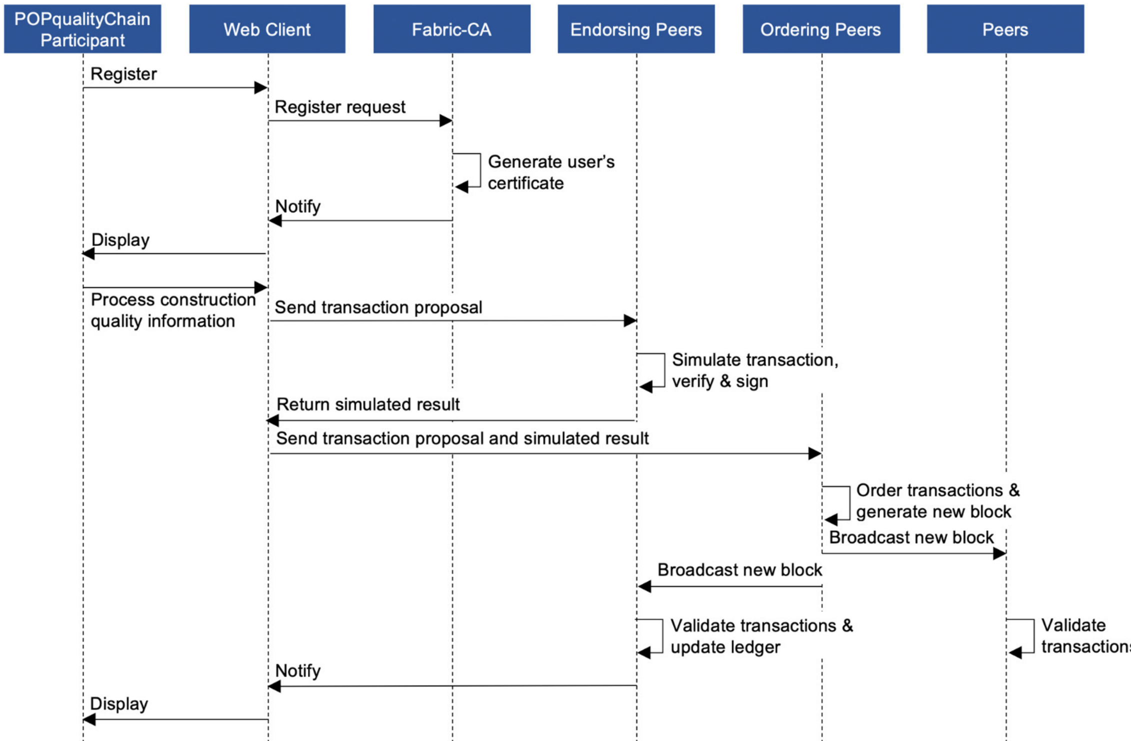

Fig. 11. Execution process on the POPqualityChain.

perform all the experimental works. Furthermore, we adopted the Docker engine (version 19.03.3) for the docker running environment and Docker Compose (version 1.13.0) for creating isolated networks and configuring docker containers. Hyperledger Fabric (version 1.4), the open-source Hyperledger framework hosted by Linux Foundation, was used for our system. Moreover, Go (version go1.11 Linux/amd64) was installed to implement the client software development kit (SDK) and smart contracts.

In the prototype system, four organizations are deployed: (1) the orderer, which is acted by the government and provides the ordering service; (2) the owner; (3) the contractor; and (4) the supervisor. *OrdererOrgs* and *PeerOrgs* in Fig. 12(a) are the configuration information for the peers in orderer and other organizations, respectively. After these peers are configured, each peer's certificates can be generated with the Cryptogen—a certificate generation tool that is commonly used for testing and demonstration in Hyperledger Fabric, including

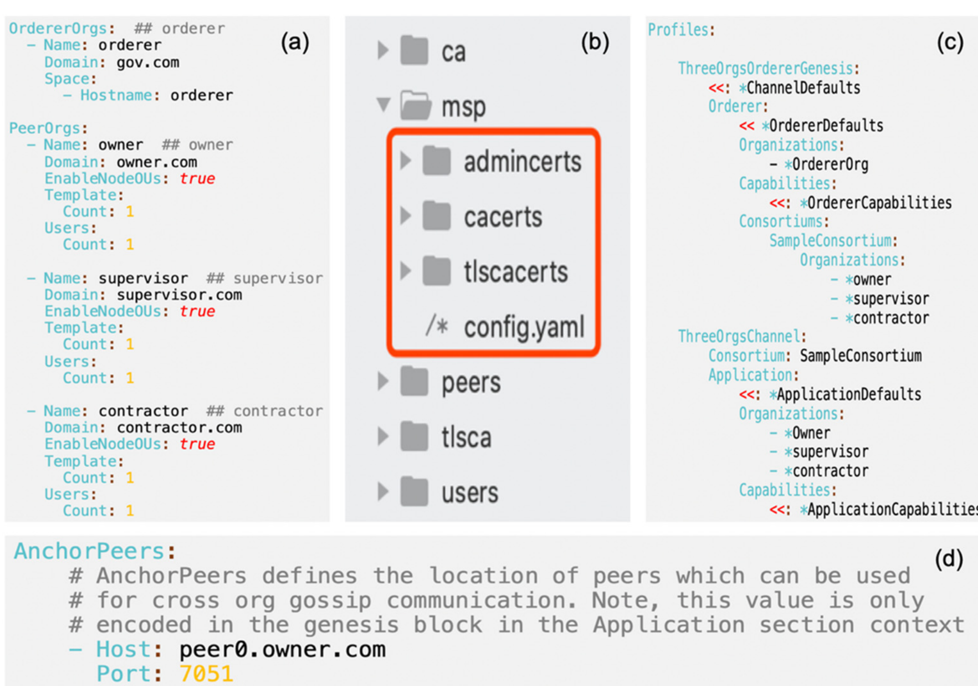

Fig. 12. Screenshots of system configuration: (a) participant configuration; (b) certificate configuration; (c) genesis block configuration; (d) anchor peer configuration.

admincert, *cacert*, and *tlscacert*. *Admincert* is the administrator identity certificate; *cacert* is the trusted root certificate; and *tlscacert* is the certificate for establishing a connection (Fig. 12(b)). Each organization is required to have an administrator registered in the Fabric CA module, such that they can obtain certificates and public–private key pair. Each administrator can then send requests to the Fabric CA for other users in his organization and obtain certificates and public–private key pair, which are used for subsequent quality information processing transactions, such as query and submission. Subsequently, genesis block, the starting point of the POPqualityChain, is configured, including ordering service information, consortium information, and organization information (Fig. 12(c)). In addition, each organization needs to designate a peer as an anchor peer for cross-organization communication in the POPqualityChain network, whereas other organizations obtain the address of the anchor peer and use it as the entry point for communication. The anchor peer is specified by the *AnchorPeers* section in the configuration file (Fig. 12(d)).

As mentioned in Section 4.2.3, an endorsing policy must be specified when a *chaincode* is installed. The endorsing policy ensures that a transaction will only take effect if the received endorsements meet the requirements. When a peer receives a new transaction to document, it will invoke the validator to confirm whether the transaction is correctly endorsed, including the endorsement signature and the number of endorsements.

Iris and AdminLTE are used to develop the backend and the frontend of the client of the prototype system, respectively. Iris is a Go-based backend development framework and is sought after by developers because it can run application with fast speed and provides rich interfaces. AdminLTE is a bootstrap-based frontend development framework that provides several reusable components for rapid development. Fig. 13(a) and (b) show the interfaces of the prototype system for information submission and query. For example, when reaching the acceptance procedure for an inspection lot of cast-in-place bored piles, a quality acceptance form must be submitted to clarify the quality details and responsibilities of the inspection lot. The contractor's quality inspector can upload the field measurement data through the user interface (Fig. 13(a)). The forms are automatically generated from the custom json files by the *jsonform* plug-in; these files are extensible and can support the definition of data types and valid ranges for each attribute. After submitting the quality information and obtaining the consensus from the POPqualityChain network, the quality information is written into the latest block.

Through the quality information query interface, we can trace back the generative process of the quality information (Fig. 13(b)). In addition to the basic information of the project and the inspection lot, the transaction history of the quality information and the block details of transactions can be also queried. The transaction history covers the current and historical state of the transactions for the quality information processing. For example, the quality acceptance form shown in Fig. 13(a) is in the creating state, and the history includes all processing records for the form. Furthermore, the corresponding block details can be seen on the POPqualityChain by selecting one of the transactions. These details include the height, size, time, and hash value of the block where the selected transaction is located, as well as the hash values of the selected transaction and of the parent block.

After the user uploads the form through the client, the back-end of the client uses the SDK to interact with the *chaincode*. The *chaincode* subsequently verifies the signature and checks the validity of each data in the form before it can be uploaded to the POPqualityChain.

5.2. Performance evaluation

This section provides a preliminary performance evaluation of CQIS to assess the implementation feasibility of the POPqualityChain framework. Here, several assumptions are made: 1) CQIS serves 4000 projects simultaneously, and 2) an average of 10 forms are submitted per project per day. We set the block time as T_{block} = 20 s/block, that is, a new block is generated per 20 s for recording quality information. Thus, through approximate calculation, each block contains an average of 10 forms.

The performance metrics of the blockchain mainly includes throughput, latency, and scalability. Hyperledger Fabric performs well in the performance of the throughput and scalability, easily supporting 100,000 transactions at 200 tps and having no limit on the number of

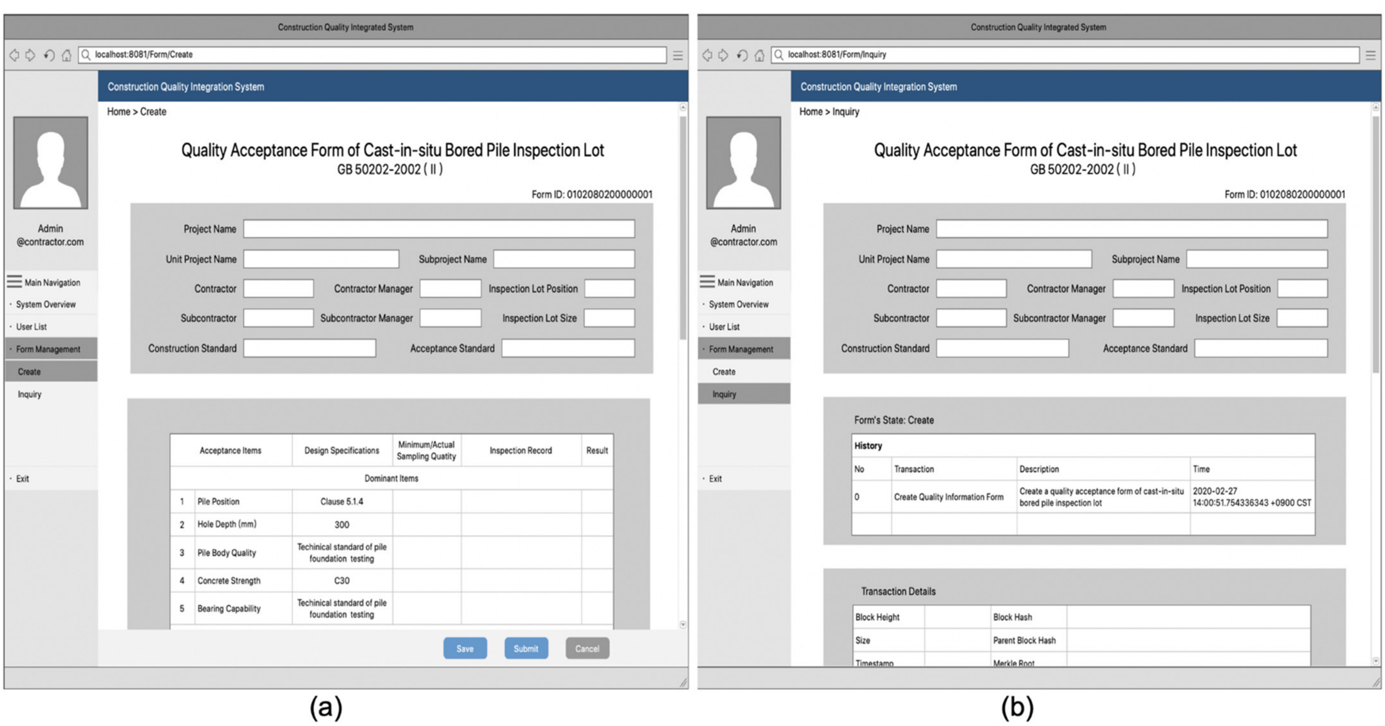

Fig. 13. User interfaces of prototype system: (1) information submission; (2) information query.

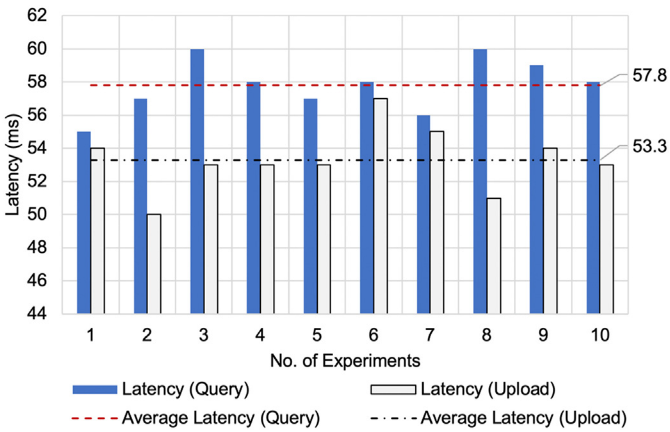

Fig. 14. Performance evaluation of the latency of the prototype system.

participants [45]. In addition, with the improvement of the hardware, network performance can be further improved. Our system is oriented to the management of construction quality information in a specific region (e.g., Wuhan), and the business volume of the system is at a low level (10 forms per block). Thus, we tested the latency of the prototype system and no longer tested throughput and scalability. We also evaluated the storage cost for applying CQIS in a real scenario. It is a meaningful metric and can reflect the computing capability that needs to be deployed by an endorsing peer for maintaining a complete ledger.

5.2.1. *Latency*

The latency performance was evaluated by measuring the round-trip time of the transactions. The round-trip time refers to the time it takes for users to send a transaction request to the blockchain network from the client to receive the transaction confirmation from the blockchain network. We tested the round-trip time of submitting quality information and querying the on-chain quality information respectively, and each type of test was conducted ten times. The system ran at the aforementioned assumed rate, that is, ten forms were submitted in one block time. The result is presented in Fig. 14. It can be seen from the result that the latency of the system is at a relatively low level, which is negligible for the user experience. Furthermore, in real application scenarios, the latency of system will also be affected by the performance fluctuations of the P2P network.

5.2.2. *Storage cost*

In Wuhan, a set of uniformed forms were adopted for recording construction quality acceptance, which are issued by construction industry regulatory authorities. A form is composed of basic information, inspection details, and acceptance results. The average size of a form is approximately 14.82 KB, as shown in Table 3. Subsequently, a Merkle Tree could be generated by performing multiple hash operations on the construction quality acceptance records in a block (Fig. 15). SHA256 hash function, which can map arbitrary sized content to a 256 bit (32 B) digest, was selected. The size of the Merkle Tree in a block is 608 B (Table 4). The header of a block includes the parent block hash, the block hash, the Merkle, root and a timestamp, and its size is 111 B; thus, the size of a block is approximately 148.86 KB (Table 4). According to the set block time, 4320 blocks were generated per day. The data generated in one day would occupy 628 MB of storage space of the endorsing peers. The storage cost caused by the data growth rate was within the acceptable range for endorsing peers.

5.3. *Case study*

The acceptance of a cast-in-situ bored pile inspection lot in a metro station project in Wuhan is used here as an example. It is an underground two-story island-style station, constructed by open-cut method, with a total length of 214.76 m, width of 19.7 m, and depth of 16.6 m. The enclosing structure of the station is a structural type of bored cast-in-place pile and internal support. The diameter of the piles is 1000 mm, the spacing is 1200 mm, and the embedded depth is 7 m.

The acceptance of 7-14# pile is implemented according to the process presented in Fig. 5. The inspection items, allowable deviation, and inspection method are specified in the Chinese code for acceptance of construction quality of building foundation (GB 50202-2018), as shown in Table 5. The framed part in Fig. 16 covers the persons responsible for the acceptance of 7-14# pile, including supervising engineer BB-011 of the supervisor, construction technician CC-011, and quality inspector CC-012 of the contractor. In accordance with the provisions of GB 50202-2018 and the responsibility division of the inspection lot, CC-012 conducts quality inspection on 7-14# pile, and the process is supervised by BB-011's side station. Subsequently, the captured quality information is signed and submitted to the CQIS system by CC-012, as shown in Fig. 17. Notably, if the submitter is not CC-012, then the system will prompt "invalid," because the corresponding permission is encoded in the pre-deployed *chaincode*, which ensures the non-repudiation of the inspection results.

After the consensus process, the quality inspection record of 7-14# pile submitted by CC-012 is written into the latest block and synchronized to the ledgers of the organizations participating the prototype system. Thus, unless unanimous consent among participants is obtained, the record can no longer be modified legally. Furthermore, Hyperledger Explorer, a web application tool, provides a visual window for monitoring blockchain. It can provide details of the network participants, blocks, and transactions. Fig. 18(a)–(c) present relevant screenshots. For our project participants, the Hyperledger Explorer provides an opportunity to backtrack the operations for processing quality information. The quality information submitted by CC-012 is contained in the transaction details in Fig. 18(c), and it is inaccessible to unrelated persons because of the permission definition in the *chaincode*. The prototype system is highly rated by the project participants. The participants are attracted by the immutability and non-repudiation of information and agree that our POPqualityChain framework and the prototype system have the potential to improve quality management in construction.

6. Discussion

Blockchain is currently on the cusp of a major technological revolution, and this study aims to explore the potential of this technology in managing quality information in the construction industry.

However, to apply the proposed POPqualityChain framework into practice, we are still confronted with the following challenges.

- The proposed framework is established on the premise that the participants can reach an agreement on applying blockchain to manage quality information. However, how to reach the agreement is a challenge. Specifically, some issues need to be discussed, such as cost apportionments for the initial development.
- The data on the chain have a strong tamper-proof capacity, but no guarantee exists that fraudulent data will not be uploaded. In the proposed framework, although confirmation and signatures from multiple parties are required to mitigate this risk when data are uploaded, completely avoiding the upload of fraudulent data for private gains through bribery and collusion remains difficult. Thus, more optimized management methods should be considered; for example, critical data can be captured and uploaded with an unattended manner (e.g., sensors-based or IoT-based methods).

In addition, the application of the consortium blockchain in the construction industry faces several general challenges.

Table 3
Size calculation of a construction quality acceptance record.

Item	Data type	Size	Item	Data type	Size
Basic information					
Form ID	Varchar	8 B	Form number	Varchar	8 B
Project number	Varchar	20 B	Unit project name	Varchar	250 B
Subproject name	Varchar	250 B	Contractor enterprise code	Varchar	18 B
Certificate type of project manager	Varchar	1 B	Certificate number of project manager	Varchar	18 B
Professional contractor enterprise code	Varchar	18 B	Certificate type of project manager of professional contractor	Varchar	1 B
Certificate number of project manager of professional contractor	Varchar	18 B	Inspection lot size	Varchar	200 B
Inspection lot position	Varchar	200 B	Construction standard	Varchar	50 B
Acceptance standard	Varchar	50 B		Subtotal	1110 B
Inspection details (Average of 40 acceptance items per form)					
Acceptance item number	Integer	4 B	Standard sampling amount	Integer	4 B
Actual sampling amount	Integer	4 B	Inspection record	Varchar	200 B
Inspection result	Varchar	50 B		Subtotal	10,480 B
Acceptance result					
Inspection result of contractor	Varchar	1000 B	Acceptance result of owner	Varchar	1000 B
Construction technician digital signature (public key: 256 B, sign value: 256 B, timestamp: 15 B)		515 B	Quality inspector digital signature		515 B
Supervising engineer digital signature		515 B		Subtotal	3581 B
				Total	15,171 B

- Blockchain is distinct-different from the centralized frameworks used by traditional project management systems. In this situation, managing the historical data stored in the traditional systems separately or migrating them to the chain will result in a high cost.
- At present, limited data formats can be supported to upload to the blockchain. Some valuable large files, such as video and model data, will degrade the performance of the blockchain.
- The running of smart contracts depends on predefined trigger conditions and response actions. Once deployed, they cannot be modified. Therefore, encoding smart contracts that can handle complex business and possible contingencies in the construction industry is a challenge at the beginning.
- The encoding and deployment of blockchain and smart contracts are knowledge-intensive tasks. However, the knowledge and experience accumulated in the construction industry are still scarce, especially in the early stage of the application of blockchain technology.
- The construction industry is often stereotyped by participants as a traditional industry, and they are reluctant to accept new technologies. Hence, exploring publicity methods to make industry participants accept blockchain technology in a wide spread is a challenge. In addition, the conventional thinking of maintaining the privatization of ledger needs to be transformed, which may be resisted by conservatives to some extent.
- The environment for applying blockchain has not yet been formed in the construction industry. At present, the majority of the participants is still on the sidelines; most of the research remains at the conceptual stage; and the technical standards and supportive

Table 4
Size calculation of a POPqualityChain block.

Item	Size	Quantity	Total
Header			
Parent block hash	32 B	1	32 B
Block hash	32 B	1	32 B
Merkle root	32 B	1	32 B
Timestamp	15 B	1	15 B
Subtotal			111 B
Merkle tree			
Hash Number	32 B	19	608 B
Subtotal			608 B
Construction quality acceptance records			
Construction quality acceptance record	15,171 B	10	151,710 B
Subtotal			151,710 B
Total			152,429 B

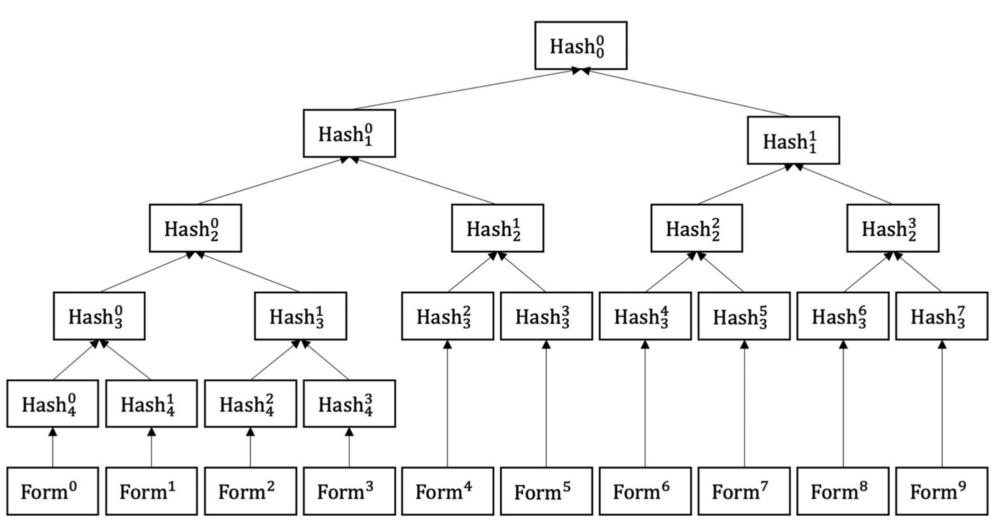

Fig. 15. Merkle tree on a POPqualityChain block.

Table 5
Inspection items and criteria of a cast-in-situ bored pile inspection lot.

Inspection items	Allowable deviation value	Method
Bearing capacity	No less than the design value	Static load test
Hole depth	No less than the design value	Using caliper to measure
Pile body integrity	/	Drilled core method
Concrete strength	No less than the design value	28-day cube strength
Rock-socketed depth	No less than the design value	Sampling inspection
Verticality	≤1/100	Using caliper to measure
Hole aperture	≥0	Using caliper to measure
Pile position	≤100 + 0.01H	Using total station to measure
Mud weight	1.10–1.25	Using hydrometer to measure
Mud level (above underground water level)	0.5–1.0 m	visual inspection
Sediment thickness	≤50 mm	Using sediment analyzer to measure
Concrete slump	180–220 mm	Using slump meter to measure
Installation depth of reinforcement cage	0–100 mm	Using steel tapes to measure
Concrete fullness coefficient	≥1.0	Calculating the ratio of the actual filling volume and the calculated filling volume
Pile top level	−50 mm to 30 mm	Leveling method

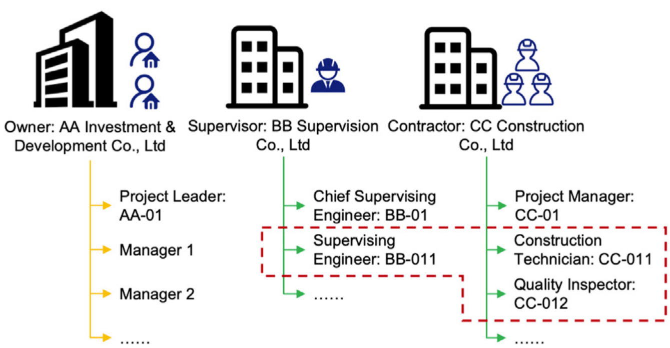

Fig. 16. Responsible persons for the cast-in-situ bored pile inspection lot.

regulations that are relied upon by technological implementation are scarce.

7. Conclusion

Accurately recording quality information in the production process can assist in coordinating project participants and reducing disputes caused by inaccurate documenting of NCRs. Due to the inequality of power, a centralized traceability system for recording of production process information in research or practice is difficult to obtain stakeholder trust. In addition, such systems have high risk of crashing, making them unattractive to participants in the construction industry.

Blockchain is a disruptive technology that aims to break the trust crisis in the distributed cooperation environment; this notion is exactly the problem that must be solved in nearly every scenario requiring the participation of multiple parties. In the scenario of quality management in construction, blockchain technology provides a new security

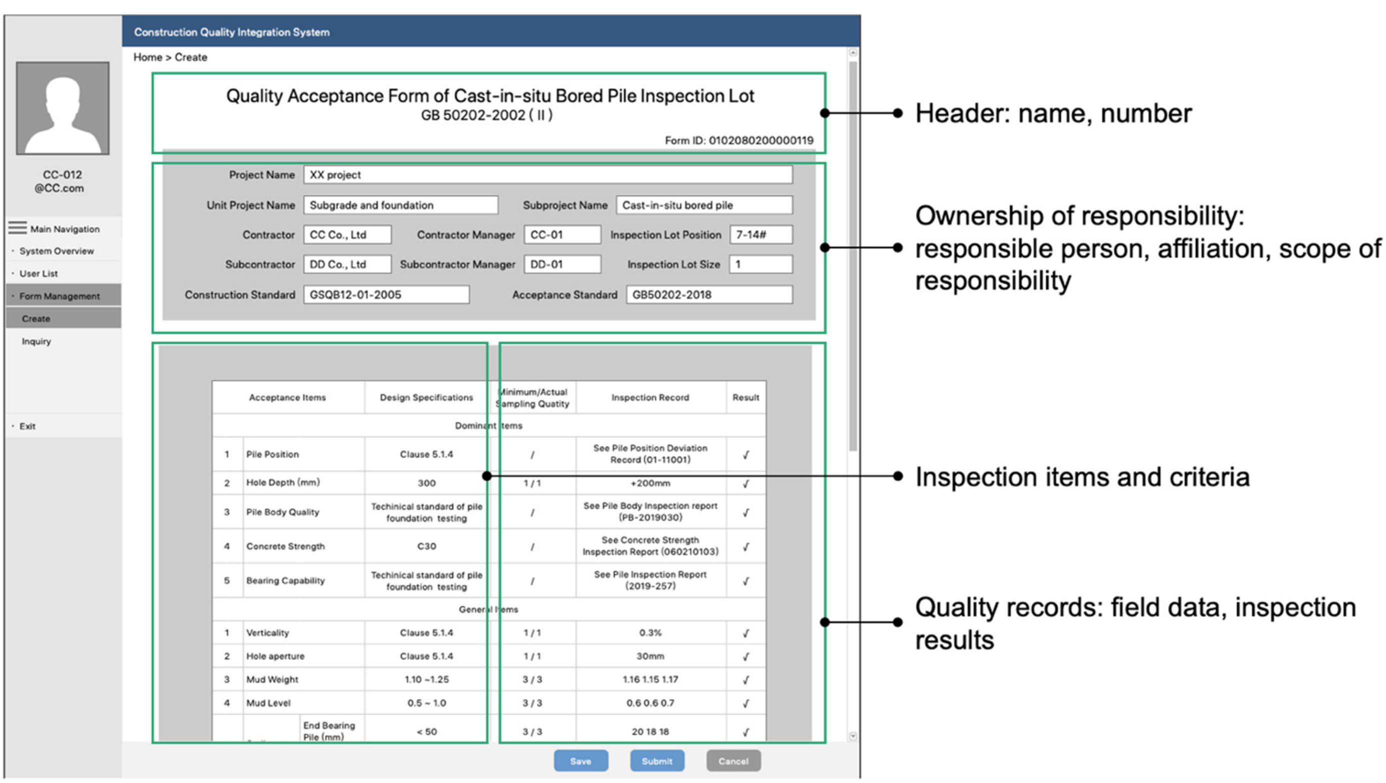

Fig. 17. Quality information recording screenshot of cast-in-situ bored pile inspection lot.

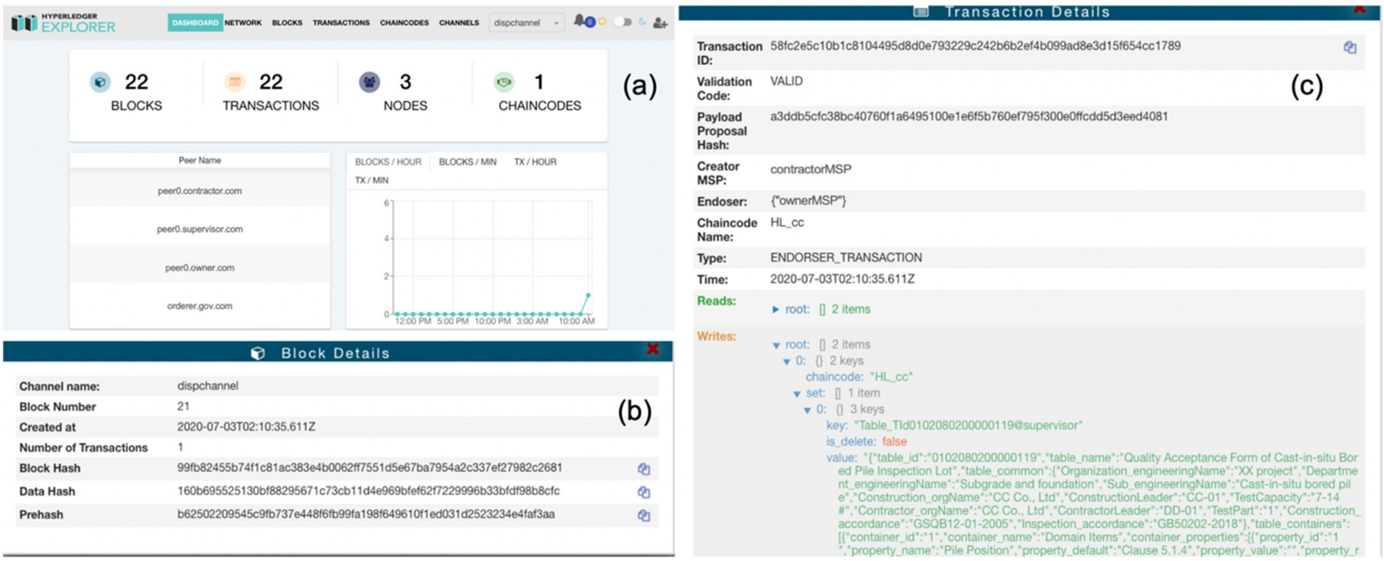

Fig. 18. Screenshots of the blockchain details: (a) network participant details; (b) block details; (c) transaction details.

protocol and infrastructure, which enable different project participants to achieve consistent, secure, and decentralized quality information management, thereby constraining the behavior of every participant.

This study presents the POPqualityChain framework for trusted quality information management in construction. The proposed framework defines clear transactions, such that the project participants (e.g., quality inspector of the contractor and supervising engineers of the supervisor) can perform their own duties and can access, process, and share the quality information on the POPqualityChain in a secure and responsible manner. A user friendly web interface is designed for user operations and shields the complex underlying logic. The preliminary performance estimation suggests that the proposed framework has the potential to be promoted and applied. This study bridges the gap for the application of blockchain technology in construction quality management. However, the limitation of this study is also evident. The feasibility of the proposed framework is only supported by limited estimation, and more evidence from practical application is needed for confirmation.

The research on blockchain technology in the construction industry is still in the exploration stage, and this study may be a beneficial attempt. In the future, in the research of construction quality information management, blockchain technology has the potential of co-evolution with BIM and IoT technologies, which will further promote industrial cooperation and improve productivity.

Declaration of competing interest

There are no conflicts of interest.

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