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RESEARCH ARTICLE

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The quality traceability system for prefabricated buildings using blockchain: An integrated framework

Abstract The quality traceability of precast components has largely affected the widespread adoption of prefabricated buildings. Blockchain technology provides an effective solution to change the centralized storage mode of traditional traceability system and its related disadvantages. In this paper, we propose a framework of quality traceability system for precast components based on blockchain technology. The system framework adopts a hybrid blockchain architecture and dual storage mode, defines three types of smart contracts, and creates an interactive and efficient source tracing query method, which could effectively achieve the goals of decentralization, openness, and non-tamperability, as well as efficient traceability.

Keywords quality traceability, precast components, blockchain, framework

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1 Introduction

Prefabricated buildings are assembled from precast components (PCs) at construction sites. This style of construction has attracted a fair amount of attention in recent years (Tam et al., 2007; Yuan et al., 2018). Prefabrication can address problems of on-site construction, provide improved quality control, protect the surrounding environment, decrease accidents, ease labor requirement, shorten construction time, reduce workload, and alleviate project complexity (Jaillon and Poon, 2008; Yin et al., 2009; Li et al., 2014; Cao et al., 2015). Because of these advantages, prefabricated buildings have been vigorously promoted as an industrial strategy for sustainable development. However, in the past few years, there has been a phenomenon known as “hot policy vs. cold market”. The market share of prefabricated buildings is still comparatively low, mainly because of obstacles such as high initial costs, lack of standard norms, shortage of skilled labor, and immature supply chains (Meiling et al., 2012; Zhang et al., 2014; Chang et al., 2018; Hong et al., 2018; Lin et al., 2018). Furthermore, with the extension of the construction site, quality problems can become more difficult to control. The potential liability disputes, delivery delays, cost increases, schedule delays, construction accidents, and public concerns limit the promotion and application of prefabricated buildings (Nahmens and Mullens, 2011; Mao et al., 2016; Ismail, 2017; Wang et al., 2019a; 2020). A traceability system is an effective method to ensure quality and would help promote high-quality development of prefabrication. Progresses in information technology (Lin et al., 2020), especially blockchain, are making quality traceability possible and adding momentum to advances in quality management for prefabricated buildings.

Blockchain provides opportunities for innovations in various fields because of its distinguishing characteristics such as decentralization, distributed storage, traceability, openness, and non-tamperability. Blockchain technology has made substantial contributions in the areas of supply chains, healthcare, and environmental governance (Till et al., 2017; Lin, 2018). It not only provides side-to-side visibility into the supply chain as well as enhanced traceability, but also offers better transparency to track product processes (Swan, 2015). As for prefabricated buildings, their supply chains are more complex than traditional ones (Wang et al., 2019b). To trace the source of product problems in a complex supply chain, a transparent and tamper-resistant metadata infrastructure is needed (Lu and Xu, 2017). Blockchain meets these conditions. In a traceability system based on blockchain, data are extracted by Internet of Things (IoT) sensors and recorded in the blockchain, which makes it possible to trace the product along the path from its source to the construction site. Machines and their operators can be traced as well (Heiskanen, 2017). Blockchain has a unique recording medium function that records the necessary information from value production to value realization (Pazaitis et al., 2017). Blockchain technology can eliminate the shortcomings of traditional quality traceability model such as centralization, low transparency, poor accessibility, and data tampering. In addition, the special features of blockchain, i.e., non-tamperability, traceability, and transparency, could promote better accountability and help improve quality management (Li et al., 2019).

In this context, we sought to develop a framework of blockchain-based PC quality traceability (PCQTA) system for prefabricated buildings. The traceability system consists of the infrastructure and interactive modules. Integrating blockchain in PCQTA allows blockchain services and function modules to be configured to enable data chaining and management. Four modules are refined to meet the requirements of prefabrication traceability and to optimize the three dimensions of traceability, namely, breadth, depth, and accuracy, to the extent possible. We adopted Radio Frequency Identification (RFID) and dual input mode to achieve the breadth of traceability. The required PC quality information is also listed. Considering the multi-party complexity of the prefabrication supply chain, hybrid architecture and hybrid consensus are proposed to maximize the depth of traceability. We also propose dual chain storage (on-chain and off-chain), data classification, smart contracts, and interaction architecture to improve the performance of blockchain for customized purposes.

The rest of the paper is organized as follows. Section 2 presents a literature review including quality issues of PCs, context of traceability, and advantages of blockchain. Section 3 presents the overall framework of the PCQTA system. Section 4 lists supporting technologies based on blockchain. Section 5 provides expert evaluation. Section 6 contains the discussion and conclusions.

2 Literature review

With the increasing promotion of prefabrication in construction, the quality of PCs has also come into focus (Yu et al., 2019). Quality problems in PC often cause a series of adverse effects on the project, such as liability disputes, schedule lags and delayed delivery, increased costs, and accidents, which hinder the adoption of prefabrication (Nahmens and Mullens, 2011; Mao et al., 2016; Ismail, 2017; Wang et al., 2020). These issues also lead to a negative public view on prefabrication, which further affects the applications of prefabrication (Wang et al., 2019a). The influencing factors of PC quality defects are more complex than cast-in-place, involving whole life cycle activities including design, production, transportation and on-site construction. In the design stage, PC entities are often not involved. Scarcity of design knowledge, lack of design standards, and mistakes by designers can cause quality defects in PCs during independent designing (Jaillon and Poon 2009; Yu et al., 2019). The PC production process is usually considered to have better quality control (Wang et al., 2015; Jiang et al., 2018), but there are still quality risks such as poor raw materials, equipment failures, erroneous processes, unfit production environments, ineffective storage management, and detrimental human interference (Ismail, 2017; Wang et al., 2018; Yu et al., 2019). Off-site manufacturing also exposes PCs to the risk of quality problems in transportation (Wang et al., 2018). Unreasonable transportation plans, maloperations by transport drivers and workers, and equipment failures may cause PC quality defects in the logistics stage (Yu et al., 2019). The construction stage of prefabrication is more complex than traditional cast-in-place processes. The artificial and mechanical operations of the hoisting and assembly processes largely determine the PC quality (Nahmens and Mullens, 2011; Yu et al., 2019). Of note, the aforementioned studies primarily focused on prefabrication quality management related to a single stage and gave limited consideration to the life cycle of prefabrication.

Quality traceability usually covers the life cycle of products to ensure traceability, and it contributes to quality control and promotes better quality management (Lin et al., 2017). The key to implementing the quality traceability process is to make objects traceable throughout the supply chain. At present, there is no consensus on the definition of traceability (Behnke and Janssen, 2019), but it is generally agreed that identifying the information that needs to be recorded and keeping records are important requirements to ensure traceability along with the ability to find this information again in the future (Moe, 1998; Karlsen et al., 2010; Thakur and Donnelly, 2010; Olsen and Borit, 2013). For traceability, it is widely accepted that it has three feature dimensions: Breadth, depth, and accuracy. Breadth indicates the amount of information collected and recorded. Depth refers to the relevant parties involved in the supply chain. Accuracy is related to the size of the tracking unit (Golan et al., 2004). Previous studies have explored the use of automatic identification and data capture technology, RFID and IoT sensors, as well as traceable resource unit and identifiable unit concepts to optimize the above three traceability feature dimensions (Dabbene and Gay, 2011; Kang and Lee, 2013; Karlsen et al., 2013; Qian et al., 2017; Fan et al., 2019; Alfian et al., 2020). Researchers have introduced distinct categories such as forward traceability and backward traceability (Olsen and Borit, 2013), voluntary and mandatory traceability (Banterle and Stranieri, 2008), active and passive traceability (Jansen-Vullers et al., 2003), and chain and internal traceability (Moe, 1998) to refine traceability. Quality traceability has been applied to many industries, such as food (George et al., 2019), tobacco (Zhong et al., 2019), steel products (Cao et al., 2020), and some precious ores (Iansiti and Lakhani, 2017). The establishment of quality traceability has improved the quality management system in these industries to a certain extent. However, few researchers have studied quality traceability in the construction sector. With respect to the built environment, lack of cooperation, insufficient information sharing, and poor trust may exacerbate the disadvantages of the traditional quality traceability model (Li et al., 2019; Wang et al., 2020). Traditional quality traceability is generally a centralized model wherein all captured information is transferred to a central database, which cannot perform openly and transparently, and the results can be questionable (Xu et al., 2019). Moreover, the centralized structure must be managed and maintained by an authoritative third party, which is vulnerable to attack, data tampering, and data breach. The distributed traditional traceability model also has the risks of data tampering and information leaks. Therefore, the traditional traceability model needs to be enhanced.

Since the publication of the Bitcoin Whitepaper (Nakamoto, 2008), blockchain has attracted much interest. Blockchain or distributed ledger technology (DLT) is essentially a decentralized database consisting of a series of linked data blocks interrelated and generated by cryptography. Because of its characteristics of non-tamperability, decentralization, openness, and traceability, blockchain technology can bring innovative applications to many fields (Crosby et al., 2016). Traceability is one of the most promising non-financial applications of blockchain. Compared with traditional centralized traceability systems, blockchain-based systems have more free access rights, high security, high information reliability, and distributed authority control (Venkatesh et al., 2020). The application of blockchain can significantly improve the transparency of quality traceability. With this logic, blockchain can be used to provide a transparent and tamper-resistant metadata infrastructure to help track the root causes of product quality problems in complex supply chains (Lu and Xu, 2017). This kind of traceability process is open and transparent, and the authenticity of traceability results can be effectively guaranteed (Wang et al., 2017; Galvez et al., 2018; Montecchi et al., 2019). At present, blockchain technology is being integrated into different traceability systems to eliminate the disadvantages of traditional traceability model (Iansiti and Lakhani, 2017; Lin et al., 2019; Xu et al., 2019).

3 Development of blockchain-based PCQTA system framework

An integrated traceability system must have the ability to file and communicate information (Thakur and Hurburgh, 2009). This means that the PCQTA system must be able to collect the corresponding data about the quality of the PCs and to make information shared or easily accessible. The traditional traceability model satisfies the above two conditions, but it requires a large amount of labor resources to confirm and coordinate updated information. Moreover, it is difficult for multiple self-owned databases to realize efficient information sharing (Chang et al., 2019). The information asymmetry in the prefabrication supply chain also increases the difficulty of PC traceability (Wang et al., 2020). Blockchain technology can realize decentralization to ensure openness and transparency of traceability. Accordingly, in this paper, we construct a framework composed of four modules that correspond to data collection, data chaining, data management, and data query. The PCQTA system is different from the traditional traceability system. Some module components and functions are refined according to the characteristics and requirements of prefabrication supply chains and PCs. For example, IoT devices are proposed for automatic information collection and hybrid architecture is designed to cope with the complexity of multiple participants in the prefabrication supply chain.

3.1 Framework of the PCQTA system

The overall framework of the PCQTA system is presented in Fig. 1. The system consists of four modules, namely, infrastructure, blockchain services, functions, and interactions. The infrastructure module is the basis of the proposed PCQTA system and is responsible for the recording, collection, temporary storage, and transmission of data. As the core of the entire system, the blockchain services module stores all of the requisites for functional operations. To facilitate querying of quality information, the main task of the functions module is to process and manage the data stored in the blockchain. All users will query through the interactions module for data tracking.

To speed up data collection and ensure accuracy, the PCQTA system is designed to integrate IoT technology,

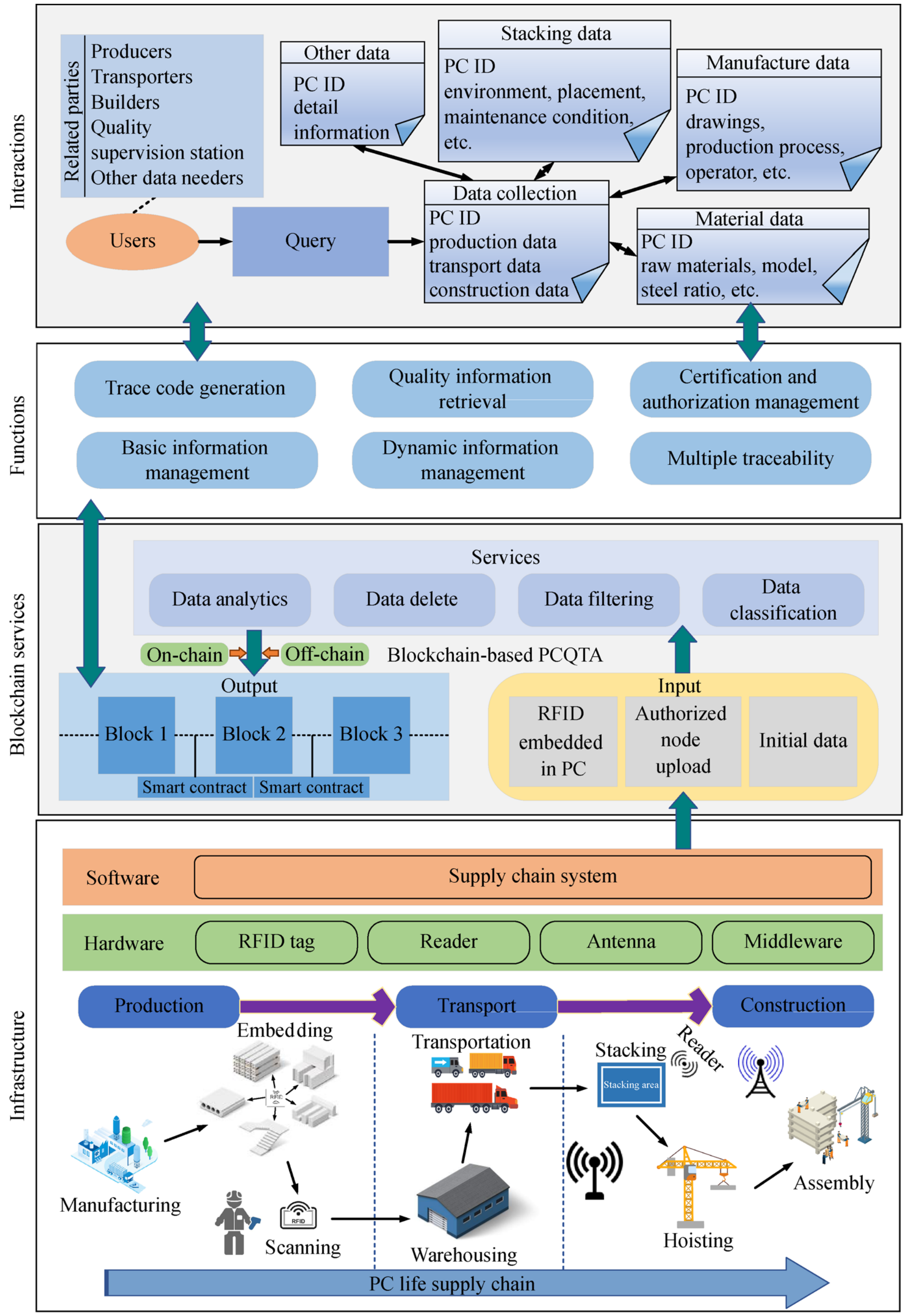

Fig. 1 Overall framework of PCQTA system.

which will significantly reduce the deficiencies caused by artificial constraints, such as time delays, erroneous lookups and data error (Heiskanen, 2017). All physical objects are equipped with electronic devices such as RFID sensors, and receiving devices so that data can be automatically collected without manual operations (Atzori et al., 2010). In our model, the underlying level of infrastructure module covers all basic hardware, including RFID tag, reader, antennas, and middleware. In prefabrication factories, RFID tags are embedded inside every PCs for information collection from the production stage including detailed information on raw materials, models, dosages, and steel ratios of the precast components. RFID writer devices are placed at key nodes in the supply chain of the PCs to input important information. A series of information particulars, such as those relating to warehousing, transportation, hoisting, and assembly, are sequentially written into the RFID tag. At the upper level of the infrastructure module, the supply chain system acts as a middleware system for data transfer between the underlying infrastructure and the blockchain services layer.

The blockchain services module is responsible for processing and storing the information uploaded by the infrastructure module. The initialized data includes two types: Data of RFIDs embedded in PCs and information uploaded by the authorization nodes with artificial assistance. All quality information from PC production, transport, and construction will be transferred to the PCQTA blockchain. Serial operations are conducted during transmission to ensure the validity and accuracy of the data written onto the block. Because of the large number of PCs in a prefabricated project and the continuing maturation of blockchain storage technology, it is currently difficult to store all of the PC information in the blockchain (Chang et al., 2019). In our system, the PCs are classified, and some of them are selected for direct upload to the blockchain (on-chain). The remaining PCs will be indirectly uploaded to the blockchain (off-chain) to ensure that the data are also traceable and cannot be modified. Data filtering is obligatory to remove the duplicate information generated by the two upload methods, so that there will be no redundancy inside the PCQTA blockchain, ensuring the internal efficiency of the system. After classification and filtering, all input data will be gathered to check for gaps to ensure that all indispensable information in the PC life cycle is written into the PCQTA system. The blockchain technology can ensure the authenticity of the information in the quality traceability process, but the data could be modified before uploading. Therefore, data analysis services are adopted to attempt to prevent this potentiality. Finally, all PC data that has been classified, filtered, cleaned, and analyzed will be stored directly or indirectly in the PCQTA blockchain and linked in a chain structure.

The functions module provides six functions in the PCQTA system to help the interactions module perform accurate and efficient information querying. These six functions are proposed according to the characteristics of the PC supply chain including information asymmetry, complexity, multi-participation, dynamics, dispersion, and non-disclosure of information (Yu et al., 2019; Wang et al., 2020). For the quality traceability of PCs, trace codes must be generated to achieve code uniqueness and avoid unnecessary queries. The participation of numerous circulators makes the admission of system nodes necessary to establish authentication and authorization management. Then, the quality information query function can be used for data retrieval to achieve the integrity of the quality traceability process. During the traceability process, the system uses multiple traceability smart contracts to broaden the breadth of traceability so that the results can cover all key points. Finally, for the PCQTA system, the management of information is divided into two types: Basic and dynamic information management. Basic information management is mainly used for input data that does not change in the PC supply chain such as PC size, performance, and materials. This type of information is considered to be unchanging during the PC production phase, while the other type of information may change to some extent or need added remarks because of special circumstances, such as change of transportation line caused by traffic jams or damage to the PC's exterior due to force majeure. These unexpected situations require dynamic information management to make the PCQTA system more specialized.

All queries in the PCQTA system are implemented in the interactions module. Relevant parties in the entire PC supply chain can perform quality traceability by entering the unique trace code. Through systematic retrieval, a data set containing all PC information will be presented to the user, and the key points of quality problems can be found by comparison with standards and specifications.

3.2 Principles of PCQTA

The traditional traceability system is generally centralized and recorded and saved separately by each participant, leading to so-named "isolated information islands". Each market participant saves PC information themselves. Because the camera is not always turned on at the critical moment, the participants may be able to alter data or lie to safeguard their interests. As such, the centralized ledger maintained by stakeholders is not reliable for traceability. Blockchain provides powerful tools for traceability in multifarious scenarios, such as anti-counterfeiting, supply chain finance, and supply chain management (Kshetri, 2018; Azzi et al., 2019). The decentralized ledger has advantageous real-time reconciliation capability in the registration and settlement aspects, as well as tamper-free and timestamp capability for the integrity of data storage (Dagher et al., 2018). To ensure our proposed system's advantages, the following requirements are imposed on data collection and database processes of the PCQTA system:

- Decentralization: It requires all information about PCs to be distributed and stored on each node of the members participating in the circulation. The issues of traditional traceability systems should be prevented, such as the loss of all information about PCs due to damage to the central database or the occurrence of various other special circumstances (Xu et al., 2019).
- Tamperability: It prevents a party or a person who masters the management rights of the database from tampering with relevant data for their own interests (Dagher et al., 2018). The issue of not being able to track the root cause of quality problems and erroneous data will be prevented.
- Traceability: It means that when a quality problem occurs, it is possible to trace the specific part of the PC error. This requires that the information and data across the

life cycle of a PC can be stored in the database in the sequence in which they are generated, and there is no missing data.

• Openness: It requires that the PCQTA system is open to all PC stakeholders, not only to related parties such as producers, transporters, and installers during the life cycle of PCs. It should also be open to the owners of the buildings assembled from the PCs. All information and data should be supervised by them and be available for them to query.

3.3 Required data of PCQTA

To ensure traceability, all relevant quality information and any other data about product or stakeholder activities at any node in the supply chain should be recorded (George et al., 2019). As shown in Fig. 2, by correlating all of the information related to the quality of the PCs across their life cycle, the PCQTA system can provide analysts with the means and methods to trace the quality control status of each batch of PCs in each process or stage of production. The entire production process of the batch of PCs can be retraced. As a result, quality problems can be easily found, which forms the basis for quality traceability and accountability of responsible parties.

During the life stages of PCs, including the periods of production, transport, and construction, a large amount of data pertaining to PC quality is generated. Details that may be crucial to identify and understand quality problems may be hidden in this massive quantity of data. Therefore, for quality traceability, it is necessary to be able to verify the integrity of the data. As shown in Fig. 3, certain PC information is indispensable in our PCQTA system. The corresponding quality-related data that needs to be uploaded into PCQTA system is given in Table 1.

Production data

PC production is the core stage of engineering quality, and the quality of prefabricated buildings depends largely on the quality of PCs themselves. Compared to the traditional model, PC manufacturers assume greater responsibility throughout the project (Yu et al., 2019). The production process consists of mold assembly, lashing of steel bars, installation of embedded parts, pouring concrete, and leaving the mold. Each stage is tracked by the responsible engineers at the production site for quality management and supervision. At the same time, relevant files (e.g., quality documents) are generated at each stage, and the production progress information is shared with the transport and the construction units for the formulation of the transportation plan and the determination and adjustment of the construction plan. Information and data directly related to the PC quality include raw material, PC, and manufacturing information. In terms of current technology, the production and manufacturing level of PCs is in its infancy, and the PCs have incomplete mechanization, low degree of automation, and low level of informatization in the production process (Jiang et al., 2018). Many human activities that affect the manufacturing quality of PCs (e.g., stepping on prefabricated steel

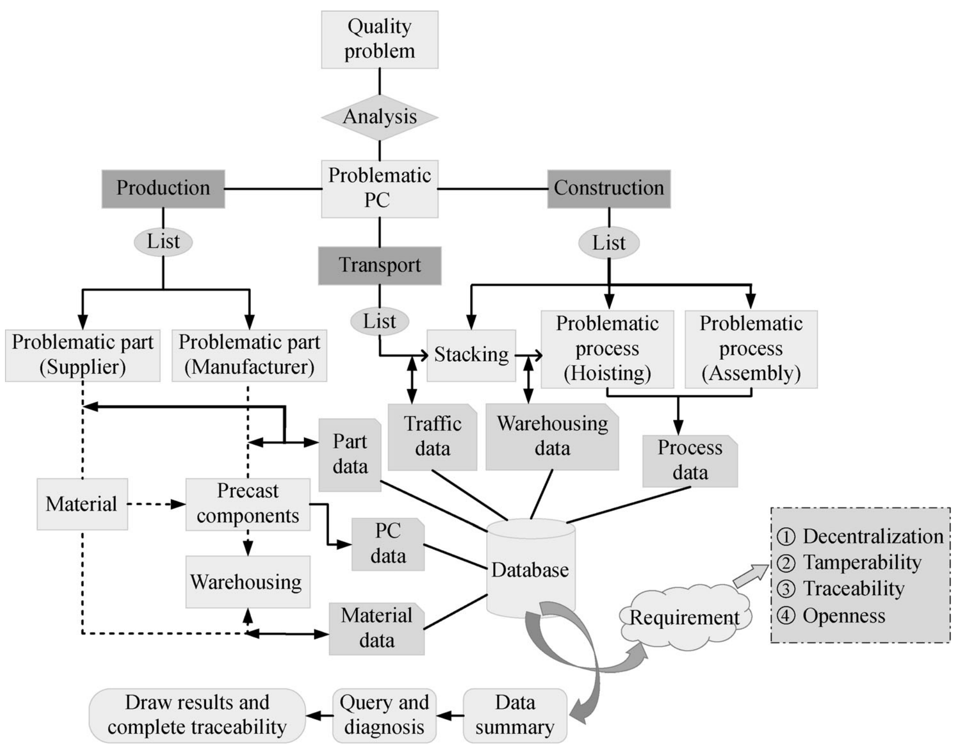

Fig. 2 Mechanism of PCQTA.

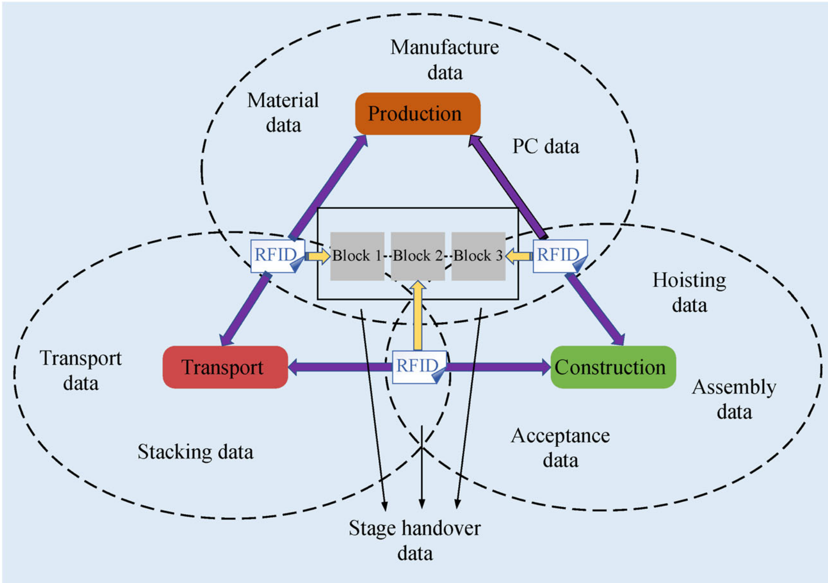

Fig. 3 Required data of PCQTA system during production, transport and construction.

Table 1 Corresponding quality-related data uploaded into PCQTA system

Data items	Details
Material data	Raw materials, model, dosage, steel ratio, additives, strength grade, etc.
PC data	Size (length, width, height, volume, etc.), performance (durability, corrosion resistance, compressive strength, flexural strength, etc.), etc.
Manufacture data	Manufacturing drawings, production process, operator, etc.
Transport data	Traffic plan, lifting equipment, vehicle type, routes, racks, loading and unloading requirements, time, etc.
Stacking data	Environment, placement method, maintenance condition, etc.
Hoisting data	Hoisting plan, hoisting machinery, hanging point design, etc.
Assembly data	Installer, installation steps, important assembly nodes, connection information, key parts control, etc.
Acceptance data	Size acceptance, appearance acceptance, process acceptance, etc.
Stage handover data	PC code, size, weight, inspection data, feedback, etc.

bars resulting in their deformation or displacement) are difficult to detect, and it is very difficult to record negative factors for quality traceability.

Logistics data

In the logistics phase, off-the-shelf PCs are transported to the construction site. The main activities in this stage are the loading, unloading, transportation, and stacking of PCs. Because of the special nature of PCs, they cannot be transported as easily as conventional building materials (Feng et al., 2015). The PCs must be transported by professional suppliers or logistics companies. Unregulated loading and unloading methods, transportation schemes that are not in accordance with the standards, and incorrect stacking environment can have significant impact on the quality of the PCs or may even damage the PCs (Yu et al., 2019). The transport stage is the intermediate link in the entire life cycle of the PC, and it is necessary to enter stage handover information data into the PCQTA system. The importance is reflected in the fact that the previous link data can be compared and verified, and it can also be the basis for the subsequent stage.

Construction data

The construction phase of PCs plays a vital role in the safety and quality of the overall structure of the prefabricated building. The construction stage of PCs has changed from a traditional construction site to a building assembly plant. The process of building houses for humans is similar to that of building things out of Lego blocks. However, the PC on-site assembly process is more complex than traditional cast-in-place processes, which means more quality issues will occur in the construction stage (Yu et al., 2019). After the PCs arrive at the construction site, they are lifted by professional lifting machinery and personnel in accordance with the lifting plan. After the PCs are fixed, they are connected and installed through the connection points. Based on the construction process of PCs, the information required for construction is divided into hoisting, assembly, and acceptance information data.

Data collection

Because traditional paper documents are used for the collection of information and data, there may be a series of problems for the quality traceability of PCs (Demiralp et al., 2012), which may include discontinuity in the quality information, gaps and omissions, difficulty in traceability, centralization, among others. Automated data collection through RFID has been extensively studied for tracking PCs (Ergen et al., 2007).

Researchers have begun to combine RFID and other tools for use in prefabricated buildings, such as integrating RFID and building information modeling (BIM) for mitigating project schedule risks (Li et al., 2017), IoT platforms for on-site assembly services (Li et al., 2018), PC tracking system using RFID and computer aided design (CAD) model (Naranje and Swarnalatha, 2019), and intelligent logistics management model based on RFID and BIM (Feng et al., 2015). By integrating RFID into a building, it is possible to make the various processes throughout the life of the building easier or even automated. If RFID is combined with other sensors and technologies (e.g., vision systems, positioning systems, and software integration), this will provide more powerful tools and features for the sector (Valero and Adán, 2016; Woodhead et al., 2018).

We propose to use RFID for primary data collection. In this way, human factors are mitigated and the objectivity of the data are guaranteed.

3.4 Blockchain deployment of PCQTA

As the key to PCQTA, the blockchain service is deployed in the middle layer of the PCQTA system to perform data storage and provide related services and functions. Blockchain currently has three forms, namely, public, consortium, and private blockchain. The public blockchain is open to anyone, and any node can download the complete blockchain data. Owing to this feature, consensus has become a big problem because of the existence of many nodes. Therefore, the public blockchain using proof-of-work (PoW) systems like Bitcoin is very inefficient in transaction processing. The consortium blockchain has greatly improved the performance of the public chain, but greatly weakened the decentralization of the blockchain because of its limitations on the number and mutual familiarity of nodes. Because of the complexity of the personnel involved in the prefabrication supply chain (the number of related parties is large and may be unfamiliar with each other) and the incomplete disclosure, it is difficult for the owner to trace the quality of the PCs (Wang et al., 2020). Therefore, the consortium blockchain is also not suitable for this purpose. The fact that the private blockchain does not have decentralization at all excludes it too. A hybrid architecture alleviates the shortcomings of single form architecture, and achieves a balance between performance and decentralization (Sharma and Park, 2018). Accordingly, we adopt a hybrid architecture of public and consortium blockchain that can interlock the two consensus mechanisms through cross-chain agreements; thus, information and data can be transferred and recognized across chains so as to overcome their respective deficiencies.

In this double chain structure, the recording of the data is mainly done by the consortium chain, and the consensus formation process is mastered by a predetermined number of nodes. For the deployment of nodes, the consortium chain nodes (core nodes) are mainly selected and matched by the relevant parties of the PC supply chain. The public chain allows all nodes (edge nodes) that want to query quality information to enter, and these nodes are not responsible for the direct processing of data to ensure the stability of the data on the chain. For block data storage, the encoded block header and body are stored in the Key–Value (KV) database, and data are stored in the form of key/value (Swan, 2015). The key corresponding to each value has a corresponding prefix. Different types of values correspond to different prefixes. In addition, we can perform on-chain and off-chain storage based on the importance of the data.

Consensus mechanism is a very important step in the blockchain deployment. The efficiency of the internal operation of the PCQTA system depends on the choice of the algorithm. Because we adopt a mix of public and consortium chains, a mixture of the two commonly used algorithms of public and consortium chains, namely, PoW and Practical Byzantine Fault Tolerance (PBFT), are also adopted in the consensus mechanism. Hybrid consensus applies two or more consensus mechanisms in the same blockchain architecture (Yu et al., 2020). There are cases of the use of hybrid consensus mechanism. For example, as the world's first hybrid consensus chain in a permissionless environment adopting a double chain structure, Truechain uses a snailchain that runs PoW and a fastchain that runs PBFT. The former generates blocks and the latter is responsible for transaction processing. Their combination makes the performance and decentralization balanced. In this system, PoW allows nodes that require data to join arbitrarily and helps select and supervise PBFT accounting nodes. The system retains the mechanism of PBFT node accounting in the consortium chain to reduce the operational complexity of the Byzantine protocol from the exponential level to the polynomial level, thus helping the PCQTA system maintain an efficient data processing state. In addition, by delegating the voting rights and supervision rights of accounting nodes to the public blockchain, PoW acts as system support to help the dynamic selection and agreement of the PBFT super nodes. In this way, the nature of super nodes' formation is transformed from a consortium chain to a public chain.

4 Supporting technology of the PCQTA system based on blockchain

For the traceability framework proposed in Section 3, we specified some of its components and modules and provided references for their implementation to make the framework operable. Here, we introduce the blockchain technology architecture of the traceability system, three types of smart contracts, and the technical architecture of the efficient query module.

4.1 Technology architecture for the PCQTA blockchain

Figure 4 shows the infrastructure of the blockchain in the PCQTA system with its five layers.

Data layer

The data layer will write the converted RFID information onto the block and ensure distributed storage. According to the timestamp, all authorized nodes in the quality traceability system can use the hash algorithm and the Merkle tree to write all of the quality information and hash values of a PC from production to transportation onto the block. All blocks are sequentially connected to the main chain to form a quality trace blockchain for the PC. The entire process requires the combination of block data, chain structure, hash algorithm, Merkle tree, and asymmetric encryption (Nakamoto, 2008).

Figure 5 depicts the block structure. Each block consists of a header and a body. The block header includes the current version number, the previous block address, timestamp, nonce (a random number), bits (the target hash value of the current block), and the Merkle root (Nakamoto, 2008). The timestamp enables the quality information of the PCs to be written onto the block and the Merkle root enables the quality tracing of the PCs. A timestamp is a time-data certification that is complete and verifiable. It can prove at which time point a piece of data existed or occurred. In the blockchain system, the miners who obtain new block mining rights insert a timestamp onto the block header when recording the data block, which is used to record the write time of the current block data. Because of this, all of the blocks can be connected to the blockchain in the order they were generated (Wang et al., 2017). The Merkle tree in the block body will process each upload with a timestamp and asymmetric cryptography. Finally, a Merkle root value is stored in the block header by the hash algorithm. Through this value, the user can trace back to any information record and the current status in the blockchain to achieve quality traceability (Lu and Xu, 2017).

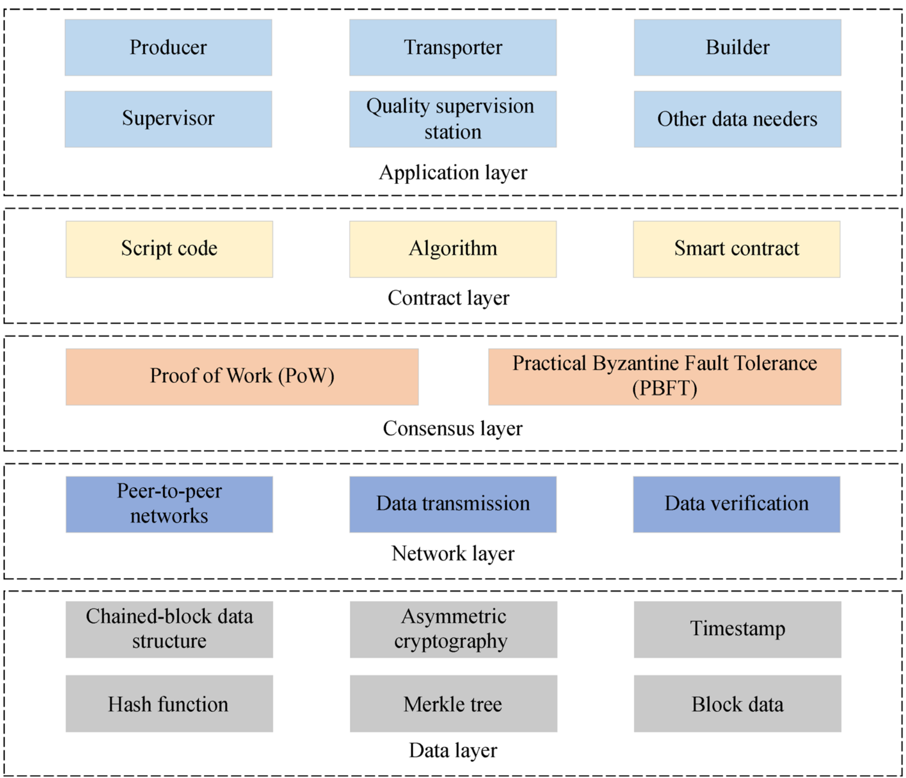

Fig. 4 Blockchain infrastructure.

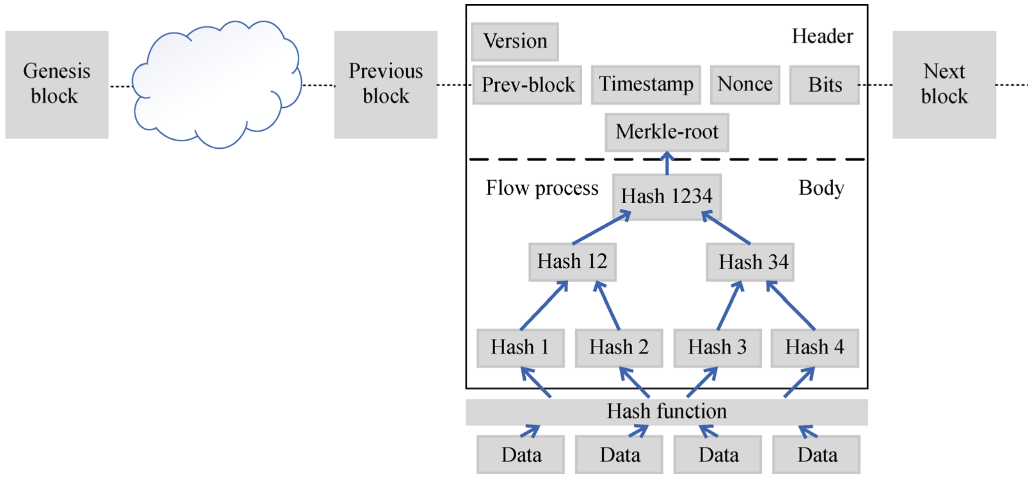

Fig. 5 Block structure.

Network layer

The network layer will enable information exchange between nodes in the blockchain network and enable decentralization of the accounting nodes. A blockchain network is essentially a peer-to-peer network. Each node receives and generates information. It is an Internet system that does not have a central server and exchanges information between nodes. In the blockchain, any node can create a new block and notify other nodes in the form of a broadcast, following which other nodes will verify the block (Wang et al., 2020). When more than 51% of the users in the blockchain network pass the verification, this new block can be added to the main chain.

The network layer is responsible for the propagation and verification of the PC data. All quality information data involved in the life cycle of the PC is linked to a specific project (i.e., the engineering project in which the PC participates) or the unique code. The networking mode of the peer-to-peer network is such that each node is connected in a flat topology (Crosby et al., 2016). To ensure the effective writing of PC information and prevent errors because of misinformation, each node must obtain the authority to access the information. The authorization center evaluates the authority of the node by the private key owned by the participant and the PC's unique code. When receiving the data uploaded after the RFID conversion, the node broadcasts to the entire peer-to-peer network. During the process of data transfer (e.g., the transportation of PCs from the warehouse to the construction site), the affiliation of the PCs changes. After agreement is reached between the two transit nodes, the digital signature and the timestamp are used to ensure that the information will not be tampered with.

Consensus layer

It is necessary to ensure timely writing of quality information onto the block. We adopt a double chain structure that is different from the mining mechanism of the public chain. We aim to unify all aspects of information. To that end, the process of mining is omitted, and the goal of achieving consensus can be realized. A consensus algorithm of Hybrid PBFT/PoW could be used for this purpose. The rational use of mixed consensus can prevent the inefficiency of a single consensus mechanism, the loss of security protection, and the sacrifice of centralization (Yu et al., 2020). The combination of the two can effectively reach a balance between centralization and efficiency.

In the consensus layer, PBFT is in the core layer, while PoW is in the edge layer, and the two layers run simultaneously to make up for the disadvantages of any single consensus mechanism. The PoW processing speed is slow; as an edge chain, it is not responsible for updating and accounting. PBFT is highly efficient; as a main chain, it is responsible for recording quality information. The PBFT nodes (core nodes) correspond to the path of PCs from producers, transporters, construction parties, quality supervision stations, and so on. The PoW nodes (edge nodes) are requesters of quality information, but are not directly related to parties such as purchasers of prefabricated buildings. The PBFT nodes will establish a phase-out mechanism: Any node that violates the security margin, such as timeouts, false accounts, or biased records, will be eliminated. The operation of this elimination mechanism is implemented using PoW. Because of the computational complexity of PBFT, the number of upper super nodes responsible for recording will not exceed 30. However, the edge layer can accept new nodes indefinitely. As a result, speed, security, and decentralization are possible at the same time.

Contract layer

In the blockchain, each block has the characteristics of programmability and embeddability. Smart contracts can be written to the blockchain and then automatically executed by all nodes on the block (Dagher et al., 2018). For this reason, the contract layer contains scripts, algorithms, and smart contracts. A smart contract often contains both data and code to make agreements and trigger contract conditions upon specific events. Therefore, it does not require manual intervention and can be automatically released when the conditions are not met. In theory, all of the terms agreed upon in advance can be triggered. Customized smart contracts can be implemented with digital codes and executed automatically without third parties under the rules and conditions preset by the entire blockchain (Guadamuz, 2019). This is the basis for the decentralization and trust of the blockchain. Smart contracts can automatically trigger execution when the constraints are reached. Therefore, in principle, smart contracts can facilitate security, trust, long-term commitments, and contractual scenarios (Zheng et al., 2020).

Application layer

All related parties, such as producers, transporters, builders, quality supervision stations, and those who need data, can enter unique codes or scan PC RFIDs through an interface to obtain all information about quality in the life cycle of the PC. If quality problems are found, they can be quickly corrected to avoid loss in the later stages (Yu et al., 2019). The corresponding responsible party can also be identified because of the comprehensive tracking of the quality information.

4.2 Smart contract

A smart contract is essentially an "if-then" statement (Guadamuz, 2019). When a smart contract is configured beforehand, it can subsequently facilitate transactions without the need of a third party. Therefore, smart contracts can reduce human intervention, save costs, improve process efficiency, and reduce risk (Zheng et al., 2020). Our proposed PCQTA system involves many participants, and the lack of trust between participants makes the assignment of operation permissions difficult. Therefore, it is objectively better and efficient for many operations in the system to be executed by smart contracts. We propose three types of smart contracts to automate some operations in the PCQTA framework. These contracts can help improve the accuracy of data uploads and traceability results, optimize the performance of the framework, and enable the stakeholders in the prefabrication supply chain to access the corresponding blockchain nodes.

Certification smart contract

The certification smart contract is responsible for authenticating all edge nodes to ensure the accuracy of data. In the PCQTA system, in order to fully upload the information of the life cycle of the PCs, the PC flow node in all links is allowed to perform data uploading functions in addition to the RFID embedded information. However, there is a risk in this approach. Any incorrect uploading of information by non-component runners will compromise the quality traceability process, and it will be challenging to find the real problem (Zhang et al., 2020). To avoid this, the certification smart contract will be set on the chain to standardize the input of PC information to ensure the accuracy of quality traceability.

All of the core nodes will adopt the PBFT consensus algorithm. When other edge nodes want to perform data upload operations, they must obtain the authorization of the core nodes. The process is as follows:

1) The edge node sends a request and the verification information to a core node;

2) The core node broadcasts a request to other core nodes, and they perform a three-stage consensus process of the PBFT algorithm;

3) After the nodes finish the three-stage process, they return a message to the edge node;

4) When the edge node receives the same message from $f+1$ nodes (where f is the number of malicious nodes), the consensus has been correctly completed. This means the authorization is obtained, and the data upload operation can be performed.

When information is uploaded to the blockchain, it will first pass the certification smart contract. The contract rules are as follows:

1) The edge node will contain the authorization of the core node. Otherwise, the contract cannot be triggered, and the data upload function cannot be performed.

2) If the same type of PC quality information appears, the RFID embedded information will prevail. Two situations, a or b, will occur:

a. The edge node is the first to write a certain type of PC data. Then, the contract is triggered after the RFID data are uploaded, and the content uploaded by the edge node is invalid or covered by the RFID information;

b. There is already some kind of information about the PC input by the RFID. The edge node tries to write the same information, and the contract is triggered, then the upload operation will not be allowed.

Classification smart contract

The classification smart contract classifies all PC information to improve system performance. At present, blockchain technology faces many technical bottlenecks. The most important of these is limited storage space, which makes it challenging to store large amounts of data. There is a need for solving the problem of limited storage space in the blockchain (Chen et al., 2019). A prefabricated building is usually made up of a large number of PCs, and quality must be traceable for every unit (Xu et al., 2018). If information related to the quality of the PCs with lower cost but higher quantity is continuously added to the block and the access rate of the block is extremely low, then the blockchain information storage is not optimally utilized (Chang et al., 2019). Using the "four quadrant rule" for analysis, the PCs can be divided into four categories according to cost and quantity as shown in Fig. 6. Among these, PCs with high cost and large and/or small quantity can be directly uploaded to the blockchain (on-chain), whereas PCs with low cost and large and/or small quantity can use IPFS (Inter-Planetary File System, another distributed network transport protocol for data upload) and blockchain improvements (off-chain) for storage (Lin et al., 2019; Liu and Li, 2020).

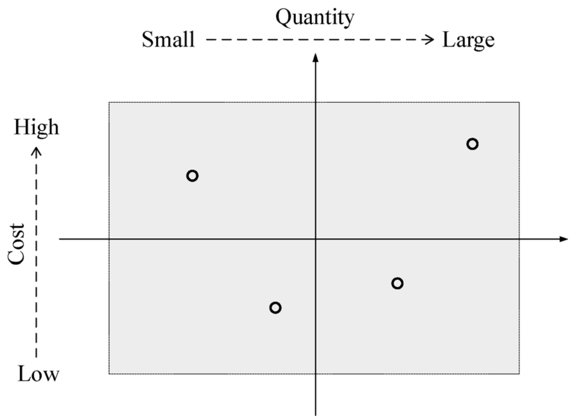

Fig. 6 PC classification.

Following data input, the classified smart contract is used to distinguish the PC types. After the PC information is uploaded, the classified smart contract written to the blockchain will be triggered, sorted according to the conditions, and selected for direct or indirect data upload.

Smart contracts will be programmed according to the following classification specification:

- Two factors, namely, cost and quantity, determine the PC classification and affect the way PCQTA system stores data;
- The unit cost of the PC is positively associated with the degree of necessity to directly upload a PC's data. The higher the PC's unit cost is, the more important it is for the whole project. Therefore, its data should be directly uploaded;
- As the quantity of a particular PC increases, the amount of data to be uploaded also increases. Therefore, the storage cost rises, leading to the inclination to not directly upload the data.

The degree of necessity (V) to directly upload a PC's data is given in Eq. (1). The other terms are as follows: Unit cost of the PC (UC), total unit cost of all PCs (TUC), quantity of individual PCs (Q), and total quantity of all PCs (TQ).

$$V = \frac{UC}{TUC} - \frac{Q}{TQ}. \tag{1}$$

If $V > 0$, then this PC's data are directly uploaded; otherwise, the data are uploaded indirectly. By selecting the most suitable upload method by such classification of PCs, the storage performance of the blockchain is optimized to ensure that information can be efficiently queried.

Multiple traceability smart contract

The multiple traceability smart contract traces the existing problem segment in a multi-directional manner, carries out multi-directional mesh tracking on the production, transport, and construction of the PCs, and quickly identifies the key points that may have problems.

- Forward traceability: When PC quality issues arise, the problematic feedback triggers the contract and selects a forward traceback. With the help of the identification and codes of the PCs at this segment, the constituent materials, basic information, production process, inventory and storage, inspection information, etc., are traced back according to the timestamp (Naranje and Swarnalatha, 2019). This helps identify the responsible party or event as well.
- Backward traceability: If there is a problem in a certain stage, such as incorrect design of PCs, unqualified raw materials, problems in the production process, or improper transportation or construction, the problematic feedback will trigger the contract and activate backward traceability. This will help trace back all of the products that have been used for this batch of PCs or raw materials and trace the flow, quantity, existing state, etc. of these products (Olsen and Borit, 2013).
- Horizontal traceability: This mainly relates to traceability of the composition of PCs, such as raw materials.
- Longitudinal traceability: Problematic PCs trigger the contract and activate the tracing of the PC production process, including manufacturing, production process, operations and operator handling, and curing time.

4.3 Quality traceability interaction

When quality information is written onto a block, the information may relate to more than one PC and may not be linked in chronological order. Therefore, it would be cumbersome to directly query all data in the life cycle of a single PC in the blockchain. Moreover, presently, blockchain transaction processing has low efficiency, low block scalability, and low direct query efficiency (Mougayar, 2016). In our method, when quality information is queried, different storage methods will be adopted according to the aforementioned classification of PCs, and a backup database will be used to speed up querying and improve efficiency. The architecture of the quality traceability interactions is shown in Fig. 7.

- Interaction interface: As a query frontend, it uses a combination of HTML (Hyper Text Markup Language), CSS (Cascading Style Sheets), and Javascript and mainly performs data uploading and data query functions.

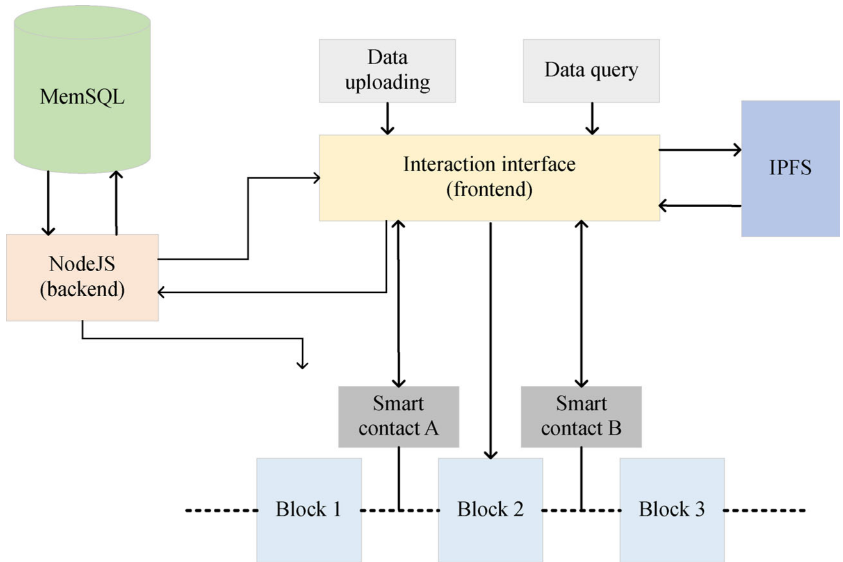

Fig. 7 Architecture of quality traceability interaction.

• IPFS: After the data are uploaded, the frontend uploads the PC code and related data that are not directly written onto the block to the IPFS and stores the hash of the returned uploaded file onto the blockchain (Lin et al., 2019; Liu and Li, 2020).

• MemSQL: Although the PC data are stored in the blockchain, it is not efficient to query the blockchain through various filters (such as displaying only certain categories of PCs or PCs that are about to pass the warranty period). MemSQL (the fastest relational database in the world capable of 1.5 million transactions per second) will be used to store PC information and query it to present PC information.

• NodeJS: This will be used in the backend server through which the frontend communicates with the database. Simple application programming interfaces (APIs) will be used to query the frontend and retrieve products from the database. At the same time, it will also be used to respond to requests for static pages of the interaction interface.

Workflow

1) Information and data stored in the RFID embedded in PCs is converted by the system and then inserted into the HTML form provided by the interactive interface. The content includes the information data required as listed in Section 3.3.

2) The interactive interface will call the contract to authenticate nodes and classify the types of PCs. If the requirements (high cost and high quantity, or high cost and small quantity) are met, the data will be directly uploaded onto the block. Other data will be stored in the IPFS for storage, the corresponding hash link will be returned, and the link will be stored in the blockchain to ensure that the information cannot be changed (Lin et al., 2019; Liu and Li, 2020).

3) This is the case when all types of PC information are directly or indirectly uploaded to the chain. The NodeJS server will listen for all events in the entire blockchain. When an event is triggered by the contract, the server reads the event content and inserts the PC information into MemSQL. This ensures that all information will be backed up in MemSQL and querying will be performed efficiently.

4) When a quality problem occurs, a quality traceability query is performed through the interaction interface. Forward traceability and backward traceability can be supported by calling a contract. The frontend will provide filtering capabilities to identify the artifacts and refine the traceability results. After receiving the request from the frontend static interface, the NodeJS server will quickly find the specific PC information data in MemSQL and return it to the frontend. In this way, it can provide quality data for specific PCs and specific stages in the quality life cycle of a PC.

5 PCQTA system framework evaluation

Two panels were established to evaluate the effectiveness and ease of use of the PCQTA system framework. Each panel consisted of five members.

Panel 1 consisted of personnel with more than five years of relevant experience in prefabrication. Considering different levels of understanding of blockchain technology in the general public, we made a detailed description of all the evaluation objects. For each object, panel members were asked to check one of the four necessity levels: “must have”, “should have”, “nice to have”, and “ok if missing” (Chou, 2003). In the end, the group discussed to reach a consensus on all of the evaluation objects.

Panel 2 consisted of experts who understand blockchain technology and have programming experience. They were asked to evaluate how difficult it would be to implement each object in the proposed PCQTA system. The evaluation process took into account their lack of knowledge regarding prefabrication and provided them clear explanations of all evaluation objects. Members were asked to check one of four difficulty levels for each object: "very difficult", "difficult", "not difficult", and "easy" (Chou, 2003). A group discussion was held to reach consensus.

Table 2 shows the results for the two panels. For the evaluation objects in the infrastructure and interactions modules, the experts in Panel 1 assigned high level of necessities and agreed that these are essential conditions for a traceability system. This is in accordance to Thakur and Hurburgh (2009)'s view that the traceability system must be able to file and communicate information. For the evaluation objects in the blockchain services and the functions modules, experts with prefabrication experience had different opinions. The experts affirmed the advantages of the quality traceability system based on blockchain, especially the decentralization, transparency, openness, and traceability. The experts regarded the proposed system as superior to traditional traceability models in those aspects. They considered 14 of the 18 objects in the blockchain services and the functions modules as necessary. The experts pointed out that the objects that improve system performance (i.e., data classification, classification smart contracts, and on-chain and off-chain storage) and the objects that expand the breadth of traceability (i.e., dual input mode) are less necessary. Compared with other products, PCs need item-level identification and data collection to achieve fine-grained management in the prefabrication supply chain (Xu et al., 2018). Experts of Panel 2 deemed that measures to improve blockchain performance are worthwhile. The current blockchain technology has the challenge of insufficient storage. If PC classification and dual storage mode (i.e., on-chain and off-chain) can be adopted, storage

Table 2 The necessity level and difficulty level of each object evaluated by two panel members

Modules	Functions/Components/Operations/Designs	Necessity level	Difficulty level of realization
Interactions	Query information	Must have	Not difficult
	Query results display information set	Must have	Not difficult
	Backup database (MemSQL)	Should have	Easy
	IPFS (off-chain)	Should have	Not difficult
	Query frontend and backend server	Must have	Easy
	Filtering capabilities	Should have	Easy
Functions	Quality information retrieval	Must have	Easy
	Trace code generation	Must have	Easy
	Multiple traceability	Should have	Difficult
	Basic information management	Should have	Easy
	Dynamic information management	Should have	Not difficult
	Certification and authorization management	Must have	Difficult
Blockchain services	Hybrid blockchain architecture (public and consortium chains)	Must have	Very difficult
	Hybrid consensus (PoW & PBFT)	Should have	Difficult
	Linked storage structure	Must have	Not difficult
	Certification smart contract	Must have	Difficult
	Classification smart contract	Ok if missing	Easy
	Multiple traceability smart contract	Should have	Difficult
	On-chain and off-chain	Nice to have	Not difficult
	Data filtering	Must have	Not difficult
	Data delete	Must have	Not difficult
	Data analytics	Must have	Very difficult
	Data classification	Ok if missing	Easy
	Dual input mode	Nice to have	Not difficult
Infrastructure	Software (supply chain system)	Must have	Difficult
	Hardware (RFID tag, reader, antenna, middleware)	Should have	Not difficult
	Data collection	Must have	Not difficult

pressure will be alleviated. However, regarding dual input mode, the Panel 1 experts viewed it as non-essential. They agreed that data collected automatically by RFID is enough and there is no need to set up nodes for manual information upload.

In Panel 2, experts mentioned that the objects identified as "easy" in the framework (e.g., query information, data filtering, and data classification) are not very difficult to implement, and these operations are no longer new. For linked storage structure, on-chain and off-chain, hardware (RFID tag, reader, antenna, middleware) and other relatively new technologies, experts in Panel 2 opined that they already have precedents for application and there are instantiable examples that can be referred to. As such, it was agreed that their implementation is not difficult. In contrast, for the objects such as hybrid blockchain architecture, hybrid consensus, and software (supply chain system), which have been employed in other practical applications, experts in Panel 2 assigned higher levels of implementation after discussion. The explanation given by the panel was that the complexity of the participants in the prefabrication supply chain makes these objects more difficult to achieve. In addition, experts pointed out that some of the operations and components such as the multiple traceability smart contracts and data analytics are too qualitative and less operable and would be difficult to instantiate with existing technologies.

Of the 27 functions/components/operations/designs, Panel 1 identified 14 (51.9%) as "must have", 9 (33.3%) as "should have", 2 (7.4%) as "nice to have" and 2 (7.4%) as "ok if missing". These experts generally believed that blockchain technology can address the limitations of traditional traceability, and the applications of RFID and other technologies will make traceability more efficient and reliable. Panel 2 marked 8 (29.6%) as "easy", 11 (40.8%) as "not difficult", 6 (22.2%) as "difficult", and 2 (7.4%) as "very difficult". Members of Panel 2 mentioned that the details, specifications, and content were comprehensive and clear, and there are application precedents of the objects.

The evaluation supported the logic and fundamentals of the proposed blockchain-based PCQTA framework. The constructive suggestions of the panelists will help drive improvements to the framework. According to the evaluation results, the proposed framework is innovative and can meet the requirements of PC quality traceability. Experts endorsed the prospects of blockchain in the domain of prefabrication traceability and deemed that the framework is promising and warrants further developments. The framework was considered as a strong reference, and panelists agreed on incorporating the objects marked with "must have", "should have", "easy", and "not difficult". Components considered unnecessary can be inserted into the system to improve overall performance if resources allow.

6 Discussion and Conclusions

Quality traceability systems have been applied to various domains and industries (Iansiti and Lakhani, 2017; Cao et al., 2020; George et al., 2019; Zhong et al., 2019). The blockchain technology is well-suited for quality traceability (Lu and Xu, 2017; Lin et al., 2019; Xu et al., 2019). We proposed an implementation framework and system architecture of the PCQTA system based on blockchain. We took into account the characteristics and requirements of PCs, supply chain, and traceability and evaluated the framework by experts in prefabrication and blockchain. Our novel framework uses distributed ledger technology for the construction industry. We constructed a blockchain-based PCQTA system that supports open, transparent, and efficient PC quality information storage, management, and traceability. Our method offers solutions and guidelines for integrating blockchain technology into the built environment and provides insights on blockchain structure design, IoT integration, data management, and performance optimization.

Theoretical and practical contributions

Our framework can improve the quality management of prefabricated buildings. The proliferation of prefabricated buildings calls for stricter quality management, especially in China (Wang et al., 2019a; Yu et al., 2019). Although China has espoused "high-quality development", the prefabrication industry suffers from quality problems because of the lack of quality control measures and tools. Establishing a quality traceability system can not only assuage the public's concerns regarding quality, but also bring many benefits to stakeholders, such as clear responsibilities, information sharing, and cost reduction. Moreover, the similarity of the prefabrication supply chain with general logistics and item-level management requirements of PC (Xu et al., 2018; Wang et al., 2020) make it feasible to adopt a quality traceability system for the management of PCs. Our research enables quality management of PCs by introducing an integrated framework to address PC traceability in the prefabrication life cycle context.

This study is also a novel example of applying blockchain technology in engineering management. The construction industry faces many challenges in adopting new technologies owing to its special built environment and the issues of low productivity, poor regulatory compliance, lack of collaboration and information sharing, and payment defaults (Li et al., 2019; Wang et al., 2020). Compared with the traditional traceability model, our proposed blockchain-based traceability model is more suitable for the built environment. Our framework facilitates an open, transparent, and efficient PC quality information traceability process. The proposed components and methods include blockchain structure design, data management, and performance optimization. As such, our framework also extends the practical research of blockchain technology implementation.

Our proposed framework serves as a valuable reference for breaking the bottleneck of blockchain applications. Although blockchain technology has made progresses in many fields in recent years, there are still several problems to be solved for practical applications. The factors restricting the applications of blockchain include the shortcomings of blockchain itself, such as performance limitations, storage limitations, synchronization limitations, governance limitations, and security issues. In addition, the complexity of the application environment also influences the applications. Our study introduces measures such as hybrid architecture, hybrid consensus, dual storage mode, off-chain storage, extended backup database, and separate chaining of classified data. Together, these features can provide a reference for applying blockchain technology in complex environments.

Managerial implications

Our framework also has important management implications. PC quality is determined by many factors. It should be examined from the perspective of the prefabrication life cycle. The production stage, which is considered to have better quality control, cannot determine the final quality of the PCs, as logistics and on-site construction are also crucial influences on the quality of the PCs. Quality traceability and assurance is a challenge for China's immature prefabrication supply chain and prefabrication technologies.

Mistrust and information asymmetry in the construction industry have always complicated project management (Lin et al., 2018; Li et al., 2019; Wang et al., 2020). Blockchain technology can greatly improve this situation. For prefabricated projects, serious consideration should be given to adopting new technologies such as blockchain to help promote information interconnection and management improvement. Project managers should consider further cooperation with universities and scientific institutions to stimulate the research and development of corresponding applications of blockchain.

As the technology of the future, prefabrication should also seek out emerging technologies. Presently, blockchain cannot achieve its full potential without integrating with other smart enabling technologies such as IoT, data visualization, and cloud computing (Zhang et al., 2020). Technologies such as BIM, RFID, and laser scanning have been widely researched and applied to prefabrication (Yin et al., 2009; Kim et al., 2015; Wang et al., 2016), which indicates that blockchain technology could be welcomed and favorably integrated, too.

Limitations and future research directions

A limitation of this paper is that the nature of the research work is conceptual and further works are needed to explore this research domain. Implementing of the proposed system requires the full cooperation of all direct and indirect stakeholders in the project. The absence of pilot projects even increases the difficulty of implementation. Instantiation and empirical testing of frameworks and systems remain open issues and future directions.

Blockchain is still a new thing for the construction industry. Implementation of the blockchain in prefabrication will face many obstacles, such as the unwillingness of conservatives to accept, and reluctance of stakeholders to share private information (Wang et al., 2020). Lack of collaboration, insufficient information sharing, and poor trust between parties may also slow down the adoption of new technology in the construction industry (Li et al., 2019). Additionally, the one-off characteristics of construction projects may reduce the willingness of stakeholders to invest in blockchain technology. The investment in blockchain can make prefabricated building that is restricted due to cost reasons even worse.

Current restrictions on the application of blockchain technology include many factors, such as storage restrictions, data authenticity (Zhang et al., 2020), throughput and delay (Wang et al., 2020), and lack of blockchain oracles (Lo et al., 2020). All these issues are far beyond the focus of this paper, namely, PC traceability problem. We have only put forward improvement schemes to some of the above issues, while detailed solutions need to be further investigated in future research.

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