Blockchain technology for governmental supervision of construction work: Learning from digital currency electronic payment systems

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Abstract

Blockchain technology has been explored for governmental supervision of construction work (GSCW) due to its merits of traceability, immutability, and transparency. However, its decentralized nature is seemingly incompatible with GSCW, which is a type of centralized governance *per se*. This research aims to find a network topology with a proper level of (de)centralization and, based on this topology, to develop a blockchain-based model for GSCW. Firstly, a literature review is conducted to identify problems in GSCW. Then, a cross-sectoral learning is performed between GSCW and digital currency electronic payment systems. Next, a design science research method is adopted to develop a dual-layer blockchain-based GSCW model integrated with an incentive mechanism. Finally, the model is illustrated in Hyperledger Fabric and evaluated its strengths and weaknesses. It is found that the model can enable an information-sharing, tamper-proof, and privacy-preserving mechanism without affecting the current status and routines of GSCW units and project teams. The model developed in our study can serve as a valuable reference for policymakers, practitioners, and researchers to develop governance policies or blockchain applications.

Keywords: Construction supervision; Blockchain; Central governance; Digital currency electronic payment; Dual-layer blockchain network.

Introduction

Central governance is where executive and legislative powers are concentrated at the top instead of scattered among lower-level governance bodies (Kooiman 2003). All constituted governments must be centralized to some degree. Even federated or federal states must exercise authority or privileges under some circumstances (e.g., the mandatory wearing of masks during the COVID-19 pandemic) (Christensen et al., 2008). Effective central governance has several advantages. It allows a clear hierarchy of reporting relationships (Corporate Finance Institute 2020). It helps reduce costs by avoiding department duplications (Bagul and Mukherjee 2018). It promotes rapid execution of decisions, as they can be made at a relatively smaller number of higher levels and then communicated to a greater number of lower levels (Ouchi 1980). Central governance can also strengthen supervision, thereby improving work quality (Lin and Ho 2013).

A typical central governance scenario can be found in the construction industry, where governmental supervision of construction work (GSCW) is usually carried out to provide an independent view on quality, safety, progress and other compliance issues (Rounds and Segner 2010; Tuuli et al. 2010). This mandatory governmental supervision of projects, including those that are privately owned, is based on public interest concerns (Li et al., 2019), and is governed by various statutory or non-statutory arrangements including national standards, construction ordinances, building codes, and professional codes of conduct (Recarte and Jaselskis 1993). For example, China's Regulations on Safety Production Management of Construction Projects require all building owners to submit documents related to project quality and safety and apply for local government construction permits (The State Council 2003). In the Australian state of Victoria, the Building Act 1993 and Building Regulations 2018 mandate that works require a building permit unless an exemption exists. Compliance with regulations such as these is overseen by government supervision units (GSUs), such as Hong Kong's Buildings Department and the Construction Commission in China, set up to issue building permits and conduct inspections as projects progress.

Blockchain technology, used most widely to record bitcoin and other cryptocurrency transactions, has been vigorously explored for its GSCW potential (Wang et al., 2020; Zhong et al., 2020). A blockchain is a distributed database with a consensus mechanism and cryptography (Risius and Spohrer 2017), with potential to offer enhanced traceability, transparency, immutability, privacy, and auditability, as well as reduced intermediary costs, among other benefits (Perera et al. 2020; Hasselgren et al. 2020). For example, blockchain allows GSUs to track the history of products and handling persons. With a blockchain-based quality and inspection platform, the scandal of missing site records will unlikely happen, and the construction quality will be more transparent to the public. In transferring control and decision-making power from a centralized entity to a distributed network, blockchain is an anti-authorization technology that counts on a consensus mechanism amongst decentralized parties. If blockchain is to be used in GSCW, the dilemma is to find a network topology that can balance centralized and decentralized governance.

Central bank digital currencies (CBDCs) provide a useful reference for blockchain in GSCW. A CBDC is a digital form of fiat money, established and regulated by a country's monetary authority (Shi and Zhou 2020). CBDCs are widely advocated because digital currencies not controlled by authorities pose problems. For example, the price of bitcoin can fluctuate sharply, affecting the financial stability of many countries (Ciaian and Rajcaniova 2016). Unsupervised digital currencies may facilitate tax evasion, terrorist financing, money laundering, and other financial crimes (Shi and Zhou 2020). To minimize these risks, the central banks of various countries (e.g., Sveriges Riksbank, the Central Bank of Uruguay, and the Central Bank of China) are developing, piloting, or have launched their own CBDCs. Particularly, in China, the central bank's digital currency electronic payment (DCEP) system has a dual-tier structure that allows the maintenance of central governance while preserving a certain degree of privacy. It seems that this and other CBDCs have found a suitable blockchain network topology to balance centralized and decentralized governance.

This research aims to find an appropriate network topology and develop a blockchain-based model for GSCW. It has four specific objectives:

1. to identify current problems in GSCW;
2. to examine and learn from China's DCEP system;
3. to develop a blockchain-based model for GSCW; and
4. to illustrate the blockchain-based supervision model through a prototype platform.

The remainder of this paper is organized as follows. The following section reviews key blockchain concepts and types and their applications in various central governance scenarios. Next, the DCEP system is introduced. The subsequent section describes our research methods. Then the findings and the proposed blockchain-based model for GSCW are presented. After that, the proposed model is illustrated through the development of a prototype system. Finally, the discussion and conclusions are presented.

Blockchain Technology

Blockchain Basics

Three key components support the functioning of a blockchain: cryptographic algorithms, a decentralized consensus mechanism, and a distributed database (Xue and Lu, 2020). Hash algorithms and Merkle trees are key concepts in cryptography, ensuring the immutability of transactions (Hasselgren et al. 2020). In the blockchain, transactions are packaged into blocks and chained together. Each block consists of a header and a set of transactions (Perera et al. 2020) (Fig. 1). The header contains an index, a hash pointer for the previous block, a hash pointer for the current block, a nonce, a timestamp, and a Merkle root. Hashing transactions indicates that the endorsed transactions are adopted as input to a hash algorithm. Then, the hash algorithm converts the transactions into unique strings (hash values). As each transaction in a block is continuously hashed and merged, the Merkle tree and final root hash pointer are formed. The hash pointer is unique for each corresponding block input, allowing verification that the current block transactions have not changed. Since the current block contains the previous block's hash pointer, blocks on the chain are not easily tampered with because changing the previous block requires changes to subsequent blocks.

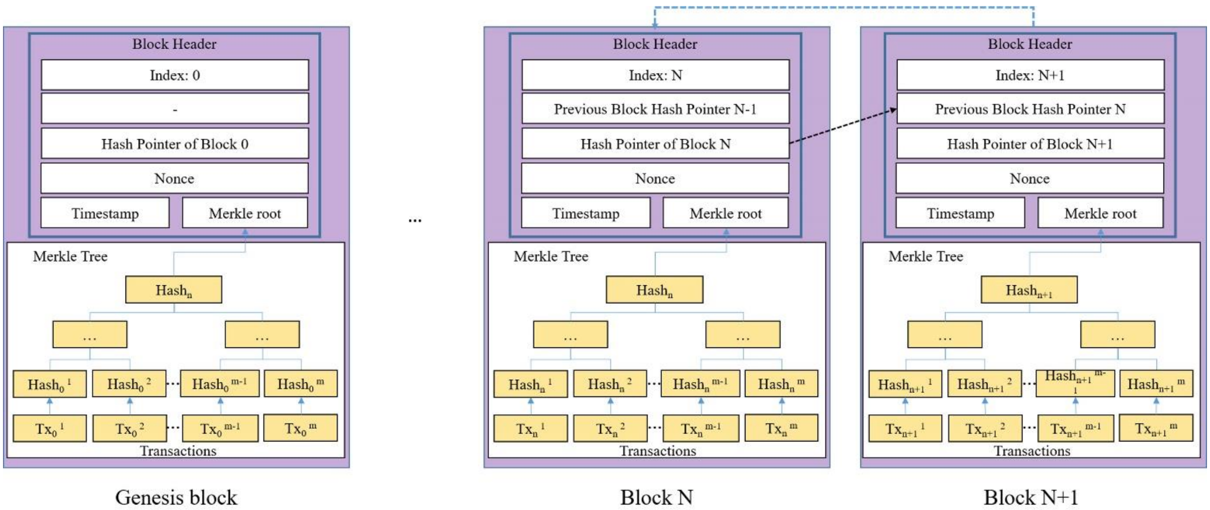
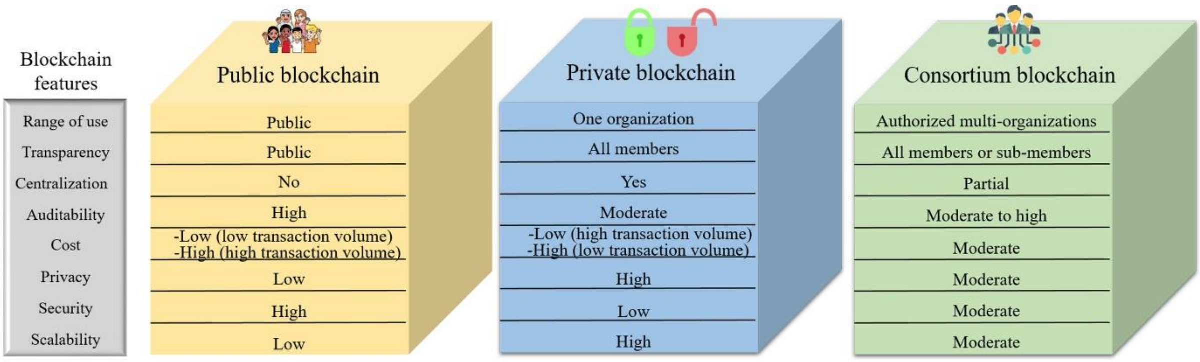


Fig. 1. An example of a blockchain

Blockchain protocol incorporates a consensus mechanism to verify the order and correctness of blocks (Hasselgren et al. 2020). That is, only when the blockchain network participants reach a consensus can transactions be included in the blockchain as a new block. Four common consensus algorithms are: proof of work, proof of stake, crash fault tolerance (CFT), and practical Byzantine fault tolerance (Perera et al. 2020). A blockchain database consisting of ledgers that record transaction data securely is distributed among network users. Peer nodes are blockchain network participants who store copies of the ledger and/or invoke smart contracts to check from or submit transactions to ledgers. As a result of the operation of these key components, blockchain information is immutable, verifiable, and trackable.

Types of Blockchain

Blockchains may be public, private, or consortium according to network centralization levels (Perera et al. 2020; Hasselgren et al. 2020) (Fig. 2). A public blockchain has a distributed and decentralized network where every interested participant can query historical transactions in ledgers or submit new transactions (Zhong et al. 2020). This network structure ensures that stored data is transparent to the public and not easily tampered with (Perera et al., 2020). However, the privacy level of a public blockchain is low because it does not provide access control functions that restrict network participants from viewing uploaded data (Hasselgren et al. 2020). Due to the need to establish trust between completely anonymous participants, an energy- and time-consuming mining-based consensus mechanism is used. This makes it difficult to improve performance of public blockchains and leads to the problem of low scalability (Perera et al. 2020).



Notes:
1. **Range of use**: the network can be used by all the public, one organization, or multiple authorized organizations.
2. **Transparency**: all the public can view the information, or only disclose the information to all members of an organization, or all members or sub-members of multiple authorized organizations.
3. **Centralization**: refers to the control of the concentration of activities. "Centralized" means that it cannot provide robustness, nor can it eliminate many-to-one traffic, leading to delays and single points of failure. "Not centralized" refers to delegating activities (especially activities related to decision-making) away from the authoritative group. For example, in a decentralized model, the transaction process of book sales will be endorsed and recorded by multiple parties (seller, buyer, and multiple certifiers). All participants have the same transaction records on their ledger to prevent fraud.
4. **Auditability**: transactions are verified and recorded on the blockchain with a timestamp, allowing users to easily track and trace previous records by accessing the ledger of any node in the distributed network.
5. **Cost**: the cost of initial platform construction, deployment, cloud storage, continuous maintenance and monitoring (high transaction volume means that the daily transaction volume is greater than 1912, and low transaction volume means that the daily transaction volume is less than or equal to 1912).
6. **Privacy**: participants' right to keep their communication and data secretly.
7. **Security**: blockchain uses encryption mechanisms involving PKI and hash algorithms to ensure the validity of stored information and prevent fraud.
8. **Scalability**: the ability to operate as usual when tasks or workloads increase.

Fig. 2. Types of blockchain

A private blockchain is managed by a single organization, and only pre-approved nodes can participate (Zhong et al. 2020). The network of private blockchains is distributed but usually to a limited extent. Private blockchains have higher privacy, scalability, and efficiency due to their more centralized nature, but transparency, auditability and security of transaction data are reduced.

A consortium blockchain involves multiple pre-authorized organizations participating in blockchain network management (Hasselgren et al. 2020). This network is partially centralized, and can allow participants full data access or set multiple levels of access permissions (Hyperledger Fabric 2020). A consortium blockchain has moderate privacy and is more auditable and secure than a private blockchain. It provides moderate scalability through its various governance structures. However, different access levels are allowed in the consortium blockchain, so participants need to spend considerable time defining these access rules.

Blockchain in Central Governance

Many blockchain studies have considered central governance. Through a scoping review, Hasselgren et al. (2020) conclude that in the health sector only 15% of blockchain studies adopt a fully decentralized structure (i.e., a public blockchain). Liang et al. (2017), however, adopt membership services supported by a consortium blockchain that allows medical institutions to issue and manage enrolment certificates and transaction certificates for access control. Yong et al. (2020) consider authority control, putting the government above enterprises, the lot release agency, and the center for disease control in their vaccine consortium blockchain system. Mao et al. (2019) use a consortium blockchain to set permissions and authentication for food suppliers, deliverers and sellers.

In construction, only a few blockchain studies have looked at central governance. In one such study, Zhong et al. (2020) utilize a consortium blockchain to supervise construction quality information, with the government a general peer node able to query transactions. Sheng et al. (2020) also use blockchain to monitor construction quality information, allowing the government to control the certificate authority (CA). Part of the blockchain network security protocol, the certificates are digitally signed and distributed by the CA and bind participants to proving their identity when conducting transactions in blockchain networks. Unfortunately, Sheng et al. do not discuss in depth why the government should maintain its central governance in issuing certificates.

While some blockchain research is dedicated to improving the traceability of the construction supply chain, it does not consider central governance. For instance, Wang et al. (2020) demonstrate a blockchain-based framework to supervise the supply chain in precast construction, but do not consider GSUs. Shemov et al. (2020) report development of a blockchain-based platform to supervise construction supply chain information and prevent manipulation, but do not provide platform access to GSUs. Qian and Papadonikolaki (2020) explain that blockchain could enable data tracking in the construction supply chain, thereby building trust between stakeholder organizations. In real-world governance scenarios, although they are interested in harnessing the power of blockchain, particularly for traceability, immutability, and information sharing, GSUs may be unwilling or not expected to give up their centralized status.

The Digital Currency Electronic Payment (DCEP) System

A central bank digital currency (CBDC) is usually accompanied by a digital currency electronic payment (DCEP) system. Unlike bitcoin, which has no central bank or intermediaries, central governance plays a pivotal role in CBDCs. China's DCEP utilizes an innovative blockchain-enabled dual-tier operation structure (Peters et al. 2020), shown in Fig. 3. At the upper level, the central bank issues DCEPs to intermediaries (e.g., commercial banks) or withdraws them. At the lower level are the transactions between intermediaries and market participants (e.g., individuals and enterprises). The main benefit of this DCEP design is that the central bank can supervise financial activities and prevent illegal transactions (Le 2020; Shi and Zhou 2020). It also allows the balance of security and privacy to achieve "controllable anonymity", i.e., only illegal activities detected will be disclosed to authorized officials, while regular transactions are anonymous (Shi and Zhou 2020). As shown by China's DCEP, central governance has become an important factor in managing digital currencies and provides a reference for harnessing blockchain power in GSCW.

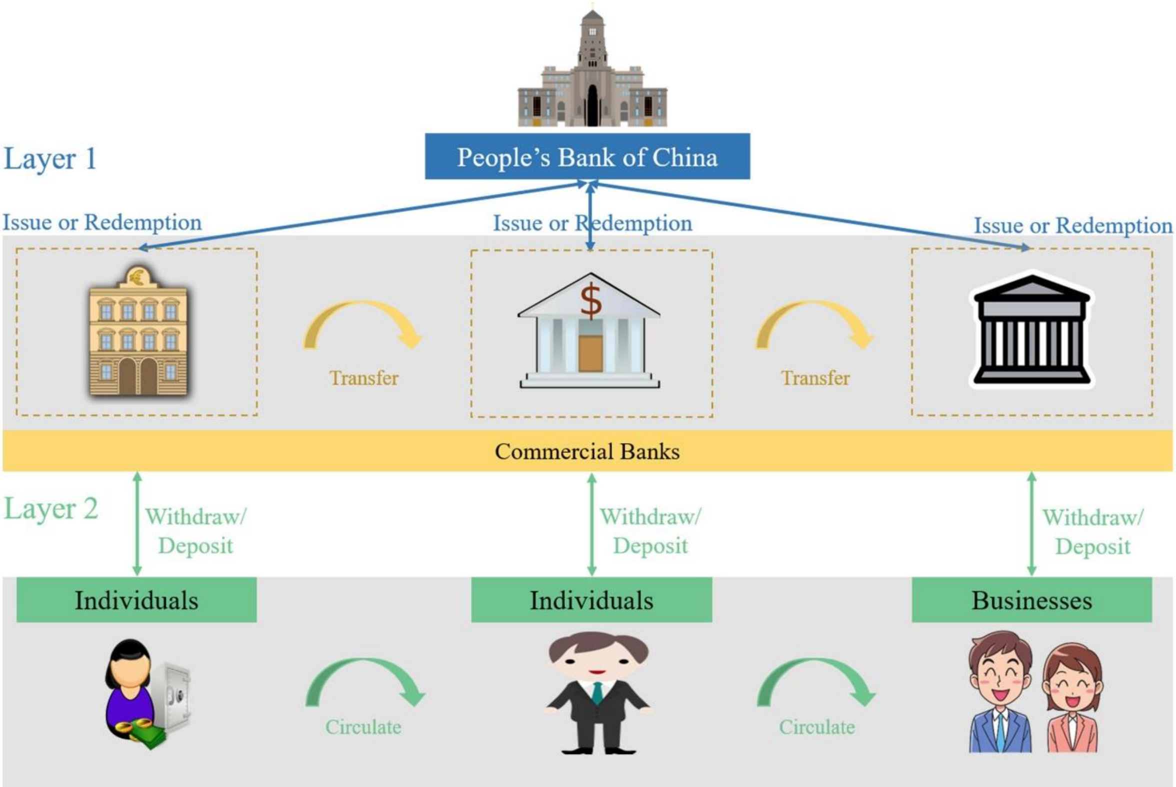


Fig. 3. A dual-tier operating system of DCEP

Research Methods

The research methodology comprises two components: literature review and design science research (DSR). The critical literature review was used to identify problems in GSCW that may be solved by blockchain technology. To search for relevant papers in Google Scholar and Web of Science databases, the keywords "blockchain in construction" and "blockchain for construction management" were used. The search initially produced 304 hits comprising journal and conference papers, books, dissertations, and reports. Titles and abstracts were screened for suitability, and hits not dealing with a specific blockchain application in construction management were excluded. The full texts of 104 selected publications were downloaded and further refined to include only those with a publication year and providing descriptive information about construction management problems and the potential of blockchain to solve these problems. This resulted in a total of 28 journal papers, 3 conference papers, and 1 industry report being collected for analysis.

Cross-sectoral learning was then conducted through another literature review round, the purpose being to understand more about DCEPs, their blockchain applications, and how (de)centralized governance is considered.

Journal articles and publicly available guidelines, white papers, and news articles were collected to analyze two aspects of DCEPs: public and central bank demands, and design features.

A DSR method was then used to develop a blockchain-based construction supervision model. DSR is an analytical and creative approach that involves creating meaningful artifacts to solve identified problems (Hevner and Chatterjee 2010). The first step was to understand our target audience; GSUs and construction project owners. The second step involved defining the critical issue; specifically, how to develop a model for a blockchain-based system enabling GSCW with an appropriate level of typology. To meet central governance requirements, the model must provide GSU with access to supervise projects. Also, the model needs to consider the privacy rights of project owners to protect their sensitive business information. The third step, in three research team meetings in October 2020, was to analyze and synthesize the knowledge gained from our literature reviews and explore solutions. Finally, the most promising solution was developed into a model prototype.

Data Analyses, Results, and Findings

Problem Identification and Blockchain Solution Potential

Table 1 summarizes the current problems in GSCW emerging from the literature review. The first problem identified is the low level of real-time information sharing (e.g., Zhong et al., 2020). Failure to share supervision information promptly has led to untimely measures and increased costs. Blockchain can improve information transparency by sharing transaction records among parties and requiring endorsements from all. The second problem relates to the low traceability of existing recording and communication methods (e.g., paper records, phone calls, and emails) (e.g., Turk and Klinc, 2017; Zhang et al. 2020). Blockchain provides a timestamp for each recorded transaction so that auditors can track the history of products and handling persons.

The lack of incentive mechanism to share information is the third problem associated with GSCW (Elghaish et al. 2020; Perera et al. 2020). If there is no incentive mechanism, project owners may not wish to disclose their project information but point fingers at each other in case of disputes. Blockchain offers a solution to this problem because it can be integrated with incentive mechanisms to encourage participation. Fourth, while the centralized storage in GSCW creates the risk of a single point of failure (e.g., Nawari and Ravindran, 2019a), blockchain can store information in a distributed manner through ledgers. A distributed database prevents file loss since the same copy of the record is replicated and stored in the node network. Fifth, without supervision, current records can be modified intentionally or unintentionally (e.g., Kim et al. 2020). Sixth, scholars such as Xiong et al. (2019) and Sharma and Kumar (2020) point out that current recording methods may involve privacy issues. By applying hash algorithms, blockchain can protect information privacy. Seventh and finally, the manual processing of GSCW information is inefficient but, with the aid of smart contracts, blockchain can automate the process.

Table 1. Current problems in GSCW and the potentials of blockchain

Problems	Blockchain potentials	Reference
Low level of real-time information sharing	Transparency	Heiskanen (2017), Wang et al. (2017), Penzes et al. (2018), Nawari and Ravindran (2019a), Nawari and Ravindran (2019b), Li et al. (2019), Yang et al. (2020), Hunhevicz and Hall (2020), Perera et al. (2020), Kiu et al. (2020), Qian et al. (2020), Zhong et al. (2020), Tezel et al. (2020), Adamska et al. (2021), Li et al. (2021).
Low traceability of paper records, phone calls and emails	Traceability	Turk and Klinc (2017), Penzes et al. (2018), Li et al. (2019), Yang et al. (2020), Perera et al. (2020), Sheng et al. (2020), Zhong et al. (2020), Zhang et al. (2020).
Lack of incentive to share information	Incentive mechanism	Perera et al. (2020), Elghaish et al. (2020).
Records are stored in a completely centralized manner, so there is a risk of a single point of failure	Decentralization	Turk and Klinc (2017), Penzes et al. (2018), Hargaden et al. (2019), San et al. (2019), Nawari and Ravindran (2019a), Perera et al. (2020), Qian et al. (2020), Zhong et al. (2020), Zhang et al. (2020).
Records can be modified intentionally or unintentionally	Immutability	San et al. (2019), Nawari, and Ravindran (2019a), Hunhevicz and Hall (2020), Perera et al. (2020), Sheng et al. (2020), Zhong et al. (2020), Kim et al. (2020), Xue and Lu (2020), Zhang et al. (2020), Shemov et al. (2020), Sharma and Kumar (2020), Adamska et al. (2021).

Current information recording and storage methods may face the risk of privacy leakage	Privacy-preserving	Turk and Klinc (2017), Li et al. (2019), Safa et al. (2019), Xiong et al. (2019), Sharma and Kumar (2020), Perera et al. (2020), Zhong et al. (2020).
Manual processing of GSCW information is inefficient	Self-execution	Wang et al. (2017), Penzes et al. (2018), Hargaden et al. (2019), Hewavitharana et al. (2019), Dakhli et al. (2019), Nawari, and Ravindran (2019b), Hunhevicz and Hall (2020), Das et al. (2020), Ahmadisheykhsarmast and Sonmez (2020), Zhang et al. (2020), Hamledari and Fischer (2021), Kochovski and Stankovski (2021).

Lessons Learned from China's DCEP System

According to Shi and Zhou (2020), the People's Bank of China (PBC) (the central bank of China, responsible for implementing monetary policy and supervising financial institutions) has the following requirements for its DCEP system: high accessibility, credibility (e.g., financial crime prevention), security (e.g., immutable data), and transaction performance (e.g., low latency). The system should also have the potential for internationalization, but the supervision power should rest with the PBC. Public user requirements are: offline payment capability, real-time payment (negligible latency), low transaction cost (low intermediary fee), high security and privacy (e.g., transaction records cannot be easily tampered with and cannot be disclosed to unauthorized parties), and official supervision (e.g., provision of a stable currency value) (Shi and Zhou, 2020). In short, the PBC must maintain central governance to supervise financial activities and prevent crime, and the public requires it to perform "business as usual" as regular commercial banks when there was no blockchain technology.

User requirements of both the PBC and the public determine the features of the DCEP system, shown in Table 2. Since DCEP is a digital payment tool with value attributes, no account is needed to realize a value transfer. Intended to replace paper money, the DCEP system must have cash-like features, including acceptance by the public. Another feature is that the PBC is legally responsible for the DCEP system, so the PBC must supervise its related financial activities to detect illegal transactions and maintain currency value. In addition, the DCEP system adopts a dual-tier operating system (Fig. 3). The first layer involves the PBC issuing DCEPs, and the second layer includes intermediaries, such as commercial banks, who distribute DCEPs to users for transactions. To minimize the potential competition between DCEPs and commercial bank deposits, the PBC does not pay interest on DCEPs. Also, the DCEP system is technology inclusive, allowing the integration of technologies besides blockchain, such as big data. A further feature of the DCEP system is that it ensures privacy through one-way anonymity, so no party other than the PBC can track the payment behaviors of users. Finally, when the Internet is not available, DCEP transactions can be made offline.

Table 2. Publications identifying salient features of DCEP

References	Digital payment	Cash-like features	Central bank's liability	Dual-tier operating system	Non-interest	Technology inclusive	One-way anonymity	Offline payment
Shi and Zhou (2020)	√	√	√	√	√	√	√	√
Peters et al. (2020)	√	√	√	√				√
Xu and Prud'homme (2020)	√		√	√				
Volkova et al. (2020)	√	√	√	√				
Wang (2020)	√		√	√		√		√
Le (2020)	√	√	√					
Feng and Borak (2020)	√	√	√	√		√		
Anwar (2020)	√	√	√	√		√	√	√
Sato et al. (2020)	√	√	√	√	√		√	√
Tran (2019)				√			√	√

By reviewing user requirements and the features of DCEP, we have summarized the points that can provide a useful reference when developing a blockchain-based model for GSCW:

- Adopting a dual-tier operating system will allow the authorities in the upper layer to increase its control over intermediaries to monitor financial crimes and maintain the stability of the overall system;
- Through the flexible structure at the lower layer, intermediaries can respond to the market and conduct efficient transactions; and
- One-way anonymity can guard user privacy.

When developing a blockchain-based supervision model, the upper layer of a DCEP dual-tier operating system can provide GSUs in construction with a central governance experience, like that of the PBC. Then, construction project owners perform similar roles to commercial banks because they are responsible for managing transactions related to individuals/enterprises or projects. In daily transactions, they all need to protect the privacy of information and enhance their ability to handle more transactions, and therefore the lower layer of the system can provide a reference for privacy and scalability design.

A Dual-Layer Blockchain-Based Supervision Model

Based on the needs of practitioners and DCEP lessons learned, this section proposes a dual-layer consensus blockchain-based model for GSCW. As shown in Fig. 4, the proposed GSCW model involves four main entities: the GSU, and construction project Owners 1, 2, and 3. Each owner should register as a peer node to record its project information and submit it to the GSU, and the GSU should register as an ordering node to order the received information into blocks and then deliver the ordered blocks to the owners for endorsement. Also, the GSU can supervise the entire project construction process for owners by seeking project and supervision information including the preliminary project information of each owner including project background and construction-related data. To avoid the fake information is deliberately input at source (i.e., the "Garbage in, Garbage out" issue), the "blockchain oracles" are used. In blockchains, an oracle is used to bridge the on-chain (i.e., a blockchain system) and off-chain worlds (i.e., a real-life physical project). It is a middleware agent *per se* that queries and endorses data from external systems to the blockchain, including for use in smart contracts (Kochovski et al., 2019). The proposed model adopts consensus-based oracles to avoid centralization issues such as a single point of failure. Thus, a *K-out-of-M* threshold signature scheme (e.g., 3-out-of-4 signature), suggested by Lo et al. (2020), is used by multiple oracles in the model to reach a consensus on the transaction to be accepted. The main blockchain involves all four entities (the GSU and Owners 1, 2 and 3). Each entity obtains a copy of the main blockchain, enabling it to supervise each transaction representing an operation in the main blockchain, such as submitting new project information or updating existing information. When all participants agree on correctness of project information via the consensus algorithm, they can endorse the operation with a digital signature.

The proposed model uses CFT consensus algorithm, which will not unduly degrade performance (e.g., transaction throughput) (Hyperledger, 2020). It does not require cryptocurrencies like Bitcoin to encourage participants to conduct expensive mining to verify transactions (Perera et al. 2020). Avoiding cryptocurrency can reduce vital risks/attack vectors, and not utilizing cryptographic mining processes can lower computational energy consumption. Operations related to the main blockchain and the local project information of owners (e.g., recording procurement information) are stored in the sidechains of owners and can be retrieved using the self-executed smart contracts of the main blockchain. The details of the proposed model are explained in the following paragraphs.

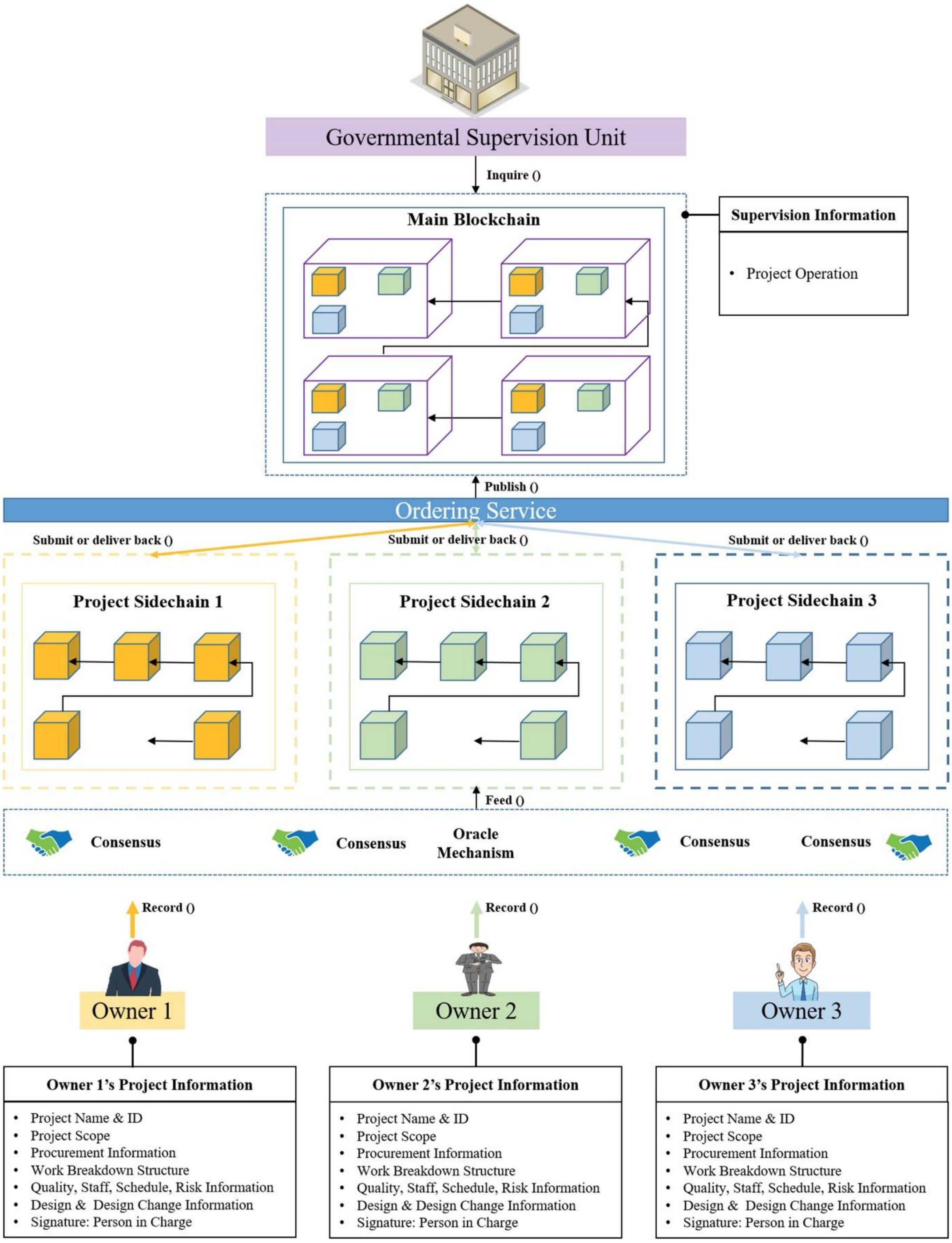


Fig. 4. A dual-layer blockchain-based model for construction supervision

As mentioned previously, the proposed model adopts a scalable dual-layer blockchain structure, including mainchain and sidechain. The dual-layer design imposes some limitations on the traditional blockchain structure. First, it retains the topology level of a GSU without significant changes to the existing regulatory system. Second, it provides privacy for different project owners, so that sensitive business information is not submitted to the mainchain. Third, the model is scalable for more project owners. Fourth, there is a mapping mechanism between operations and transactions. Construction supervision has various operations (e.g., e.g., quality inspection, progress reporting, and safety information recording) in different projects. Each operation can be matched with a specific transaction on our model, ensuring that it can handle all operations generated by different projects. Finally, the proposed model has an integrated points-based incentive mechanism.

Private operation transactions such as project procurement records and risk information can be recorded in the sidechain of each owner, inaccessible to other owners in the main blockchain. The structure of a private transaction is shown in Fig. 5(a). Each transaction includes a timestamp, the signature of the person in charge, the hash pointer, the hash pointer of the previous operation, and the data. The data is given in the form of a hash table with unique keys and values. The keys indicate the owner numbers corresponding to operations. The values display objects containing data content, such as project names and IDs and quality information. The sidechain layer contains local project information, copies of the main blockchain. Each owner maintain its own sidechain in this layer. For the main blockchain, each block consists of a header and transaction. Each block header includes an index (block sequence number in the chain), a timestamp, the signatures of the three project owners and the GSU, and the current and the previous blocks' hash pointers. As shown in Fig. 5(b), project information of the three owners is retrieved from their sidechain through their respective hash pointers. Smart contracts are installed in the main blockchain so that the GSU can retrieve operation records from the main blockchain, and owners can submit operation records at specific time intervals for construction project supervision.

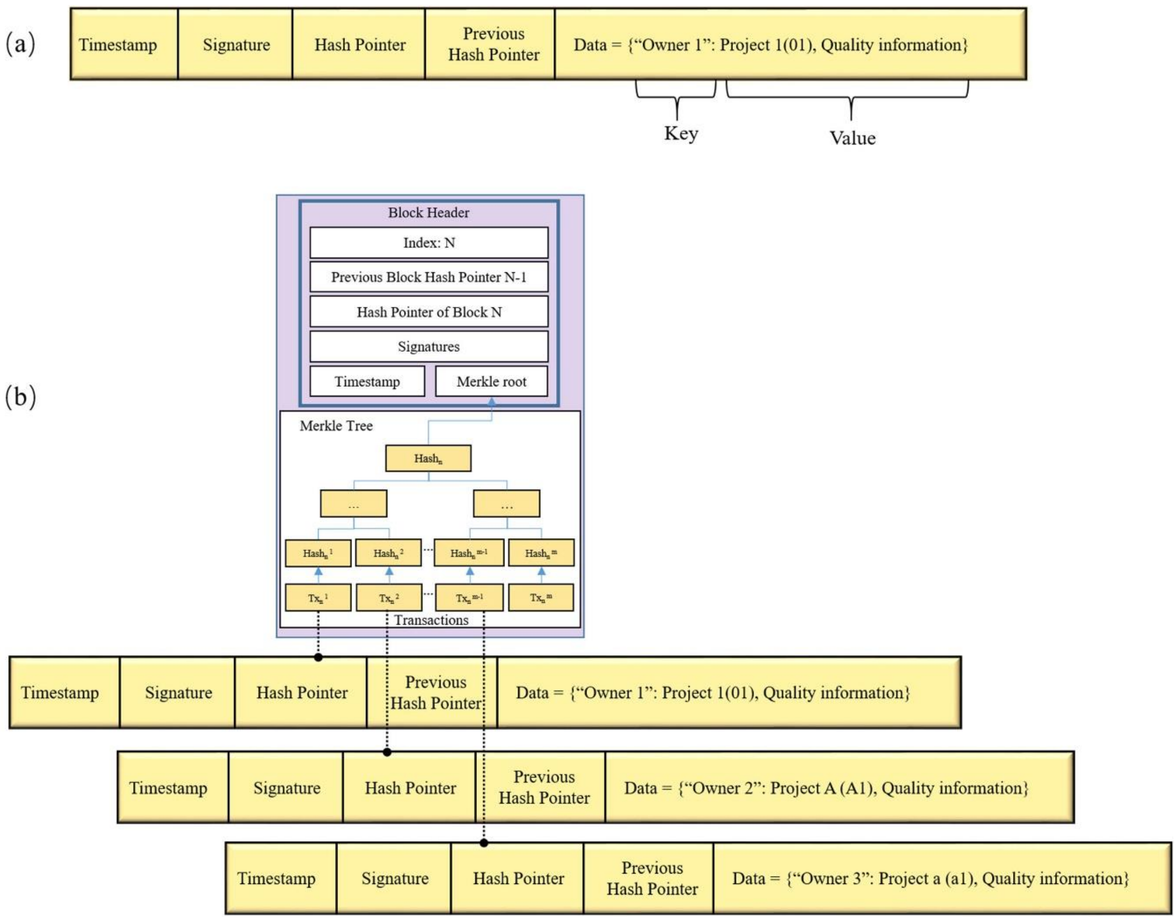


Fig. 5. Blockchain and transaction: (a) transaction structure in the sidechain; and (b) block structure in the main blockchain

As the success of the proposed blockchain-based model depends on the participation of users, a points-based incentive mechanism is integrated with the model. This mechanism aims to increase participants' willingness to publish transactions on time. Owners are informed of the details of the mechanism in advance. Table 3 shows the calculation principles for rewarding points. In this study, the owner will receive a point for each submitted transaction. Among them, each transaction published within 24 hours after completing the operation will help an owner earn 20 points. The final points are the sum of the points obtained from the published transaction and the on-time publishing. Five status levels (fail, pass, credit, distinction, and high distinction) are defined based on the total points earned, extending this incentive mechanism from rewards to reputation. The benefits of a good reputation include (1) more business opportunities; (2) lower marketing costs; (3) more customers and sales, (4) greater revenue; (5) cost-free advertising; and (6) higher company value (Pfeiffer et al., 2012). The status levels can be displayed on the GSU's website for comparative purposes. The incentive mechanism has also been expanded by combining financial incentives, which are a way to increase productivity, reduce problematic behaviors (e.g., late assignment submissions), and improve participants' attitudes (Marteau et al., 2009). Such incentives have been widely used to encourage healthy behaviors (Volpp et al., 2009) and drive construction projects' progress (Rose and Manley, 2010). In the model, every point earned by the owner can be exchanged for one dollar from the GSU. For example, GSU requires owner 1 to publish 500 transactions. As a result, owner 1 published all the 500 transactions, of which 450 transactions were published within 24 hours after completing the operations. Then, Owner 1 will receive 9500 points (1×500 + 450×20), a reputational reward of high distinction, and a financial reward of 9,500 dollars.

Table 3. The points-based incentive mechanism

Users	Reward point for each published transaction	Total number of transactions published (variable)	No. of transactions published on time* (No. of transactions not published on time)	Reward points per transaction (on time) *	Total points**
Owner 1	1	*A*	*X* (*A*–*X*), where X<=A	20	1×*A*+*X*×20
Owner 2	1	*B*	*Y* (*B*–*Y*), where Y<=B	20	1×*B*+*Y*×20
Owner 3	1	*C*	*Z* (*C*–*Z*), where Z<=C	20	1×*C*+*Z*×20

Notes:

*Transactions published within 24 hours after corresponding operations are completed.

**Total points<5000, Fail; 5000<= Total points < 6500, Pass; 6500 <= Total points < 7500, Credit; 7500 <= Total points < 8500, Distinction; 8500 <= Total points, High Distinction;

Illustration of the Blockchain-Based Supervision Model

The supervision process for our prototype system illustrating the proposed dual-layer blockchain-based model for GSCW includes registration, submit-inquire, ordering, and consensus (Fig. 6). Before joining the system, owners must first verify their identity through the GSU at the registration stage. The GSU retains the CA and issues certificates to each owner so that they can participate in the main blockchain. The submit-inquire mechanism allows the GSU to supervise the project information of owners. For example, Owner 1 can record and hash the latest quality information in its sidechain and then submit the transaction hash to the GSU while ensuring data privacy. Next, in the ordering service stage, the GSU packs the received transaction hashes into blocks and then continuously delivers the ordered blocks back to the owners for endorsement. When owners receive these ordered blocks, they should endorse the order of blocks by checking the hash pointer of the current block and the hash pointer of the previous block. In the consensus stage, all main blockchain entities can endorse the authenticity of transactions in the received blocks through the CFT consensus algorithm. Each entity can decide whether the transactions are valid or not by signing in the received blocks. In CFT, as far as there are $N / 2 + 1$ participants left in the network (N is the total number of participants), a consensus can be reached (Hyperledger 2020). All transactions are stored in blocks, even if they are not genuine, but the main blockchain copy of each owner will only update valid transactions.

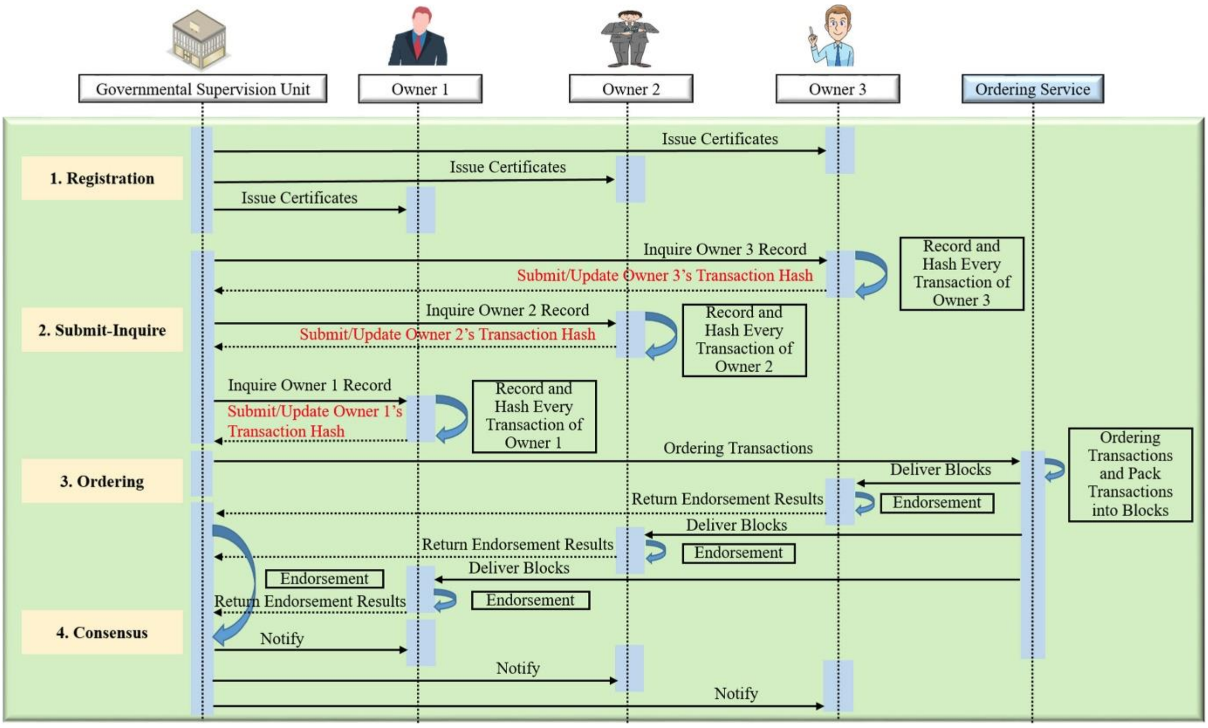


Fig. 6. Supervision process in the proposed dual-layer blockchain-based system

We used Hyperledger Fabric (version 2.2) to develop the blockchain prototype system for construction supervision, and JavaScript writing the smart contracts. Hyperledger Fabric is a blockchain platform created by the Linux Foundation. Linux version 5.4.0-58-generic-lpae (5.4.0-58.64~18.04.1) (Ubuntu 18.04.1 LTS) with four Intel® CoreTM i7-8250U CPU @ 3.40GHz processors, and 8 GB 2133MHz DDR4 memory was used to develop the application. We used the Docker engine (version 19.03.13) to develop the environment for maintaining chaincode (in Hyperledger Fabric, smart contracts are packaged as chaincode), and Docker-Compose (version 1.21.2) to form isolated networks and configure the Docker container. Four entities are involved in the prototype system: (1) the GSU, which acts as the ordering node in the ordering service; (2) Owner 1; (3) Owner 2; and (4) Owner 3. The configuration information of these entities is shown in Fig. 7(a), and the cryptogen in Hyperledger Fabric was used to achieve registration by issuing certificates (*admincert* for the administrator of each entity, *cacert* for the CA of each entity, and *tlscacert* for building connections), as shown in Fig. 7(b).

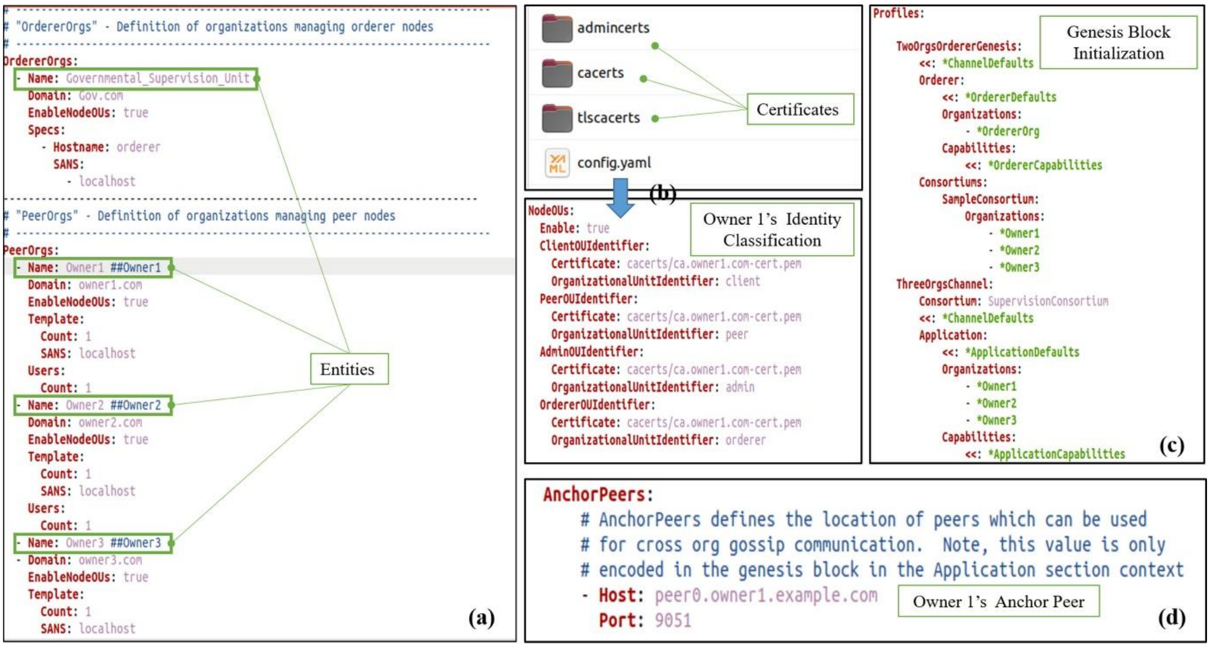
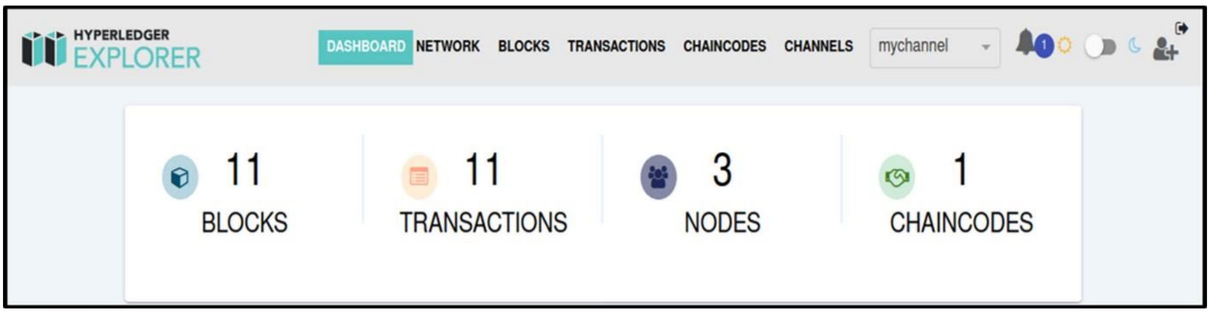
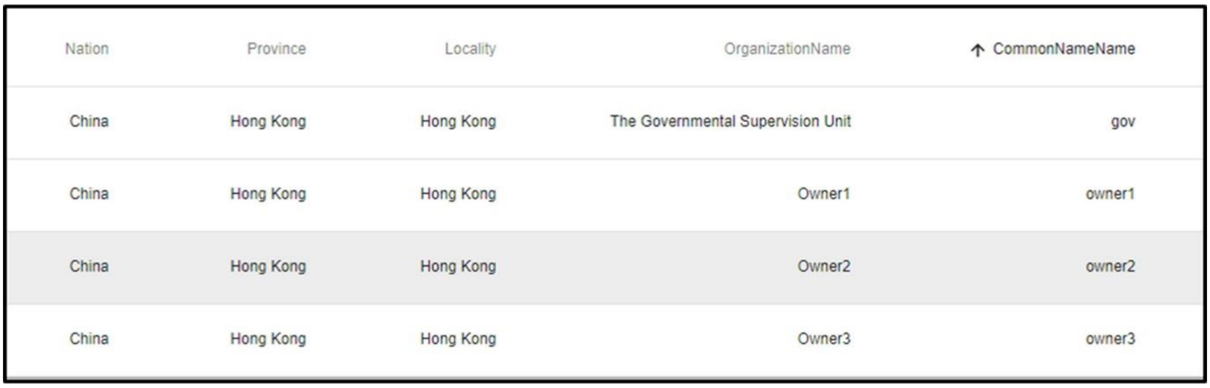


Fig. 7. Prototype system configuration for: (a) entities; (b) certificates; (c) genesis block; and (d) anchor peers

Each of the above entities has an administrator registered in the main blockchain and sidechain. Thus, entities can first obtain certificates from the Hyperledger Fabric CA module of the main blockchain. The administrator can then request the Hyperledger Fabric CA of the sidechain to issue certificates to operators of owners who record operations in the sidechain. The genesis block of the main blockchain is configured to initialize the ordering service and contains information about the consortium, and entities (Fig. 7(c)). An anchor peer is defined in each entity and used for cross-entity communication in the main blockchain and cross-chain interaction between the main blockchain and sidechains (Fig. 7(d)). Hyperledger Explorer was utilized to visualize the detailed information of the blockchain network, entities, blocks, and certificates (Fig. 8).

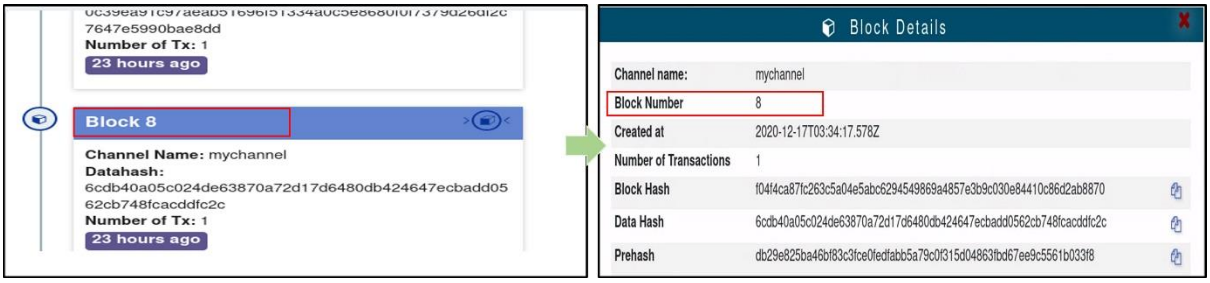


(a) network

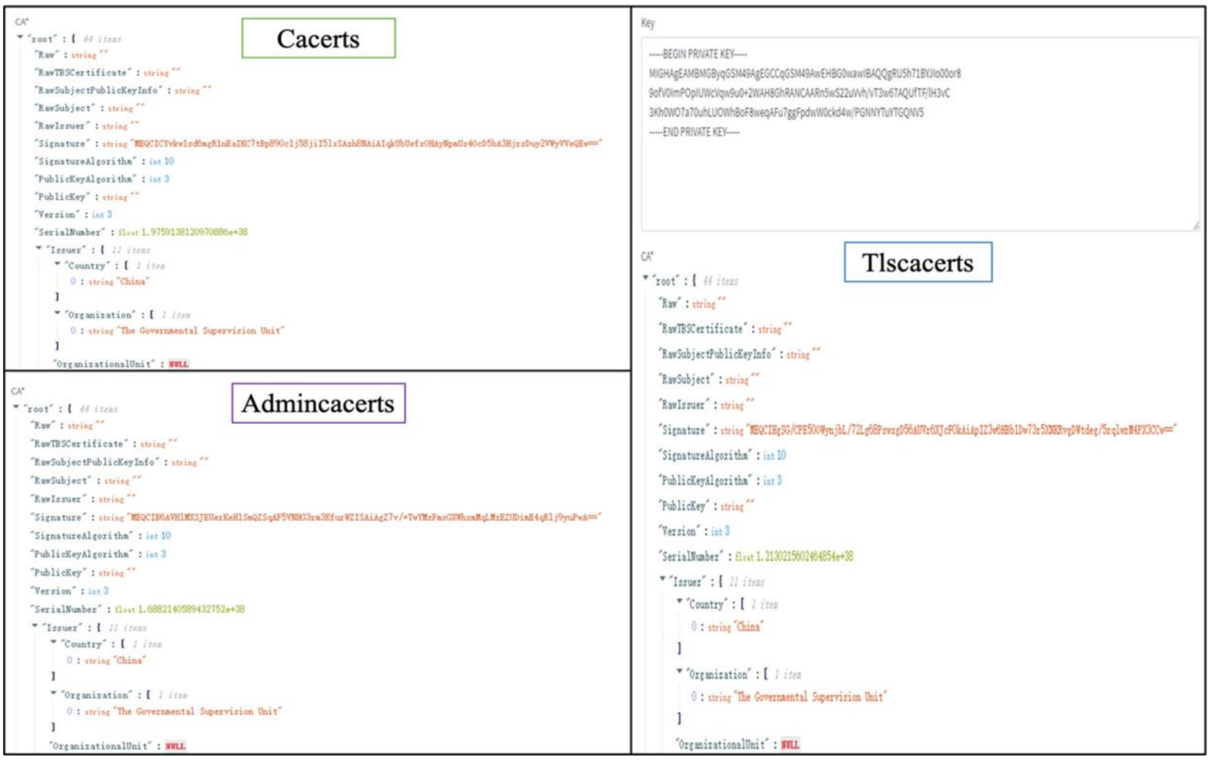


Nation	Province	Locality	OrganizationName	CommonNameName
China	Hong Kong	Hong Kong	The Governmental Supervision Unit	gov
China	Hong Kong	Hong Kong	Owner1	owner1
China	Hong Kong	Hong Kong	Owner2	owner2
China	Hong Kong	Hong Kong	Owner3	owner3

(b) entities



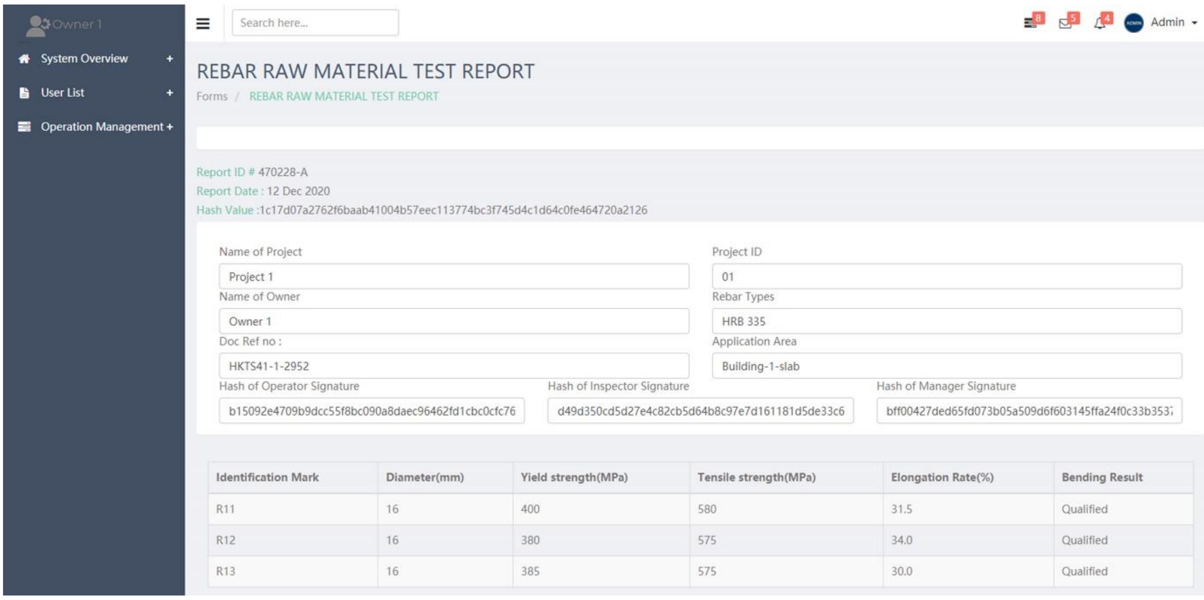
(c) block



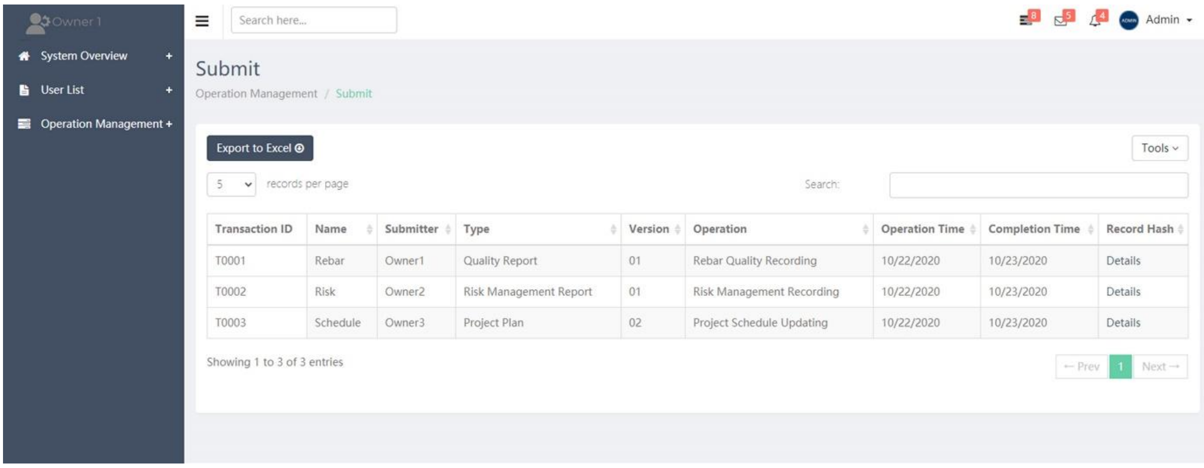
(d) certificates (GSU)

Fig. 8. Main blockchain visualization

Using SpringBoot (version 2.4.0) and AdminLTE (version 3), the backend and frontend prototypes were developed for each entity. SpringBoot, a Java-based backend framework, was used to develop a Web server and the open-source relational database management system MySQL. AdminLTE, a frontend framework based on bootstrap, provides responsive, reusable, and widely used rapid development components. Fig.9 (a) and (b) show the interfaces of the system for transaction submission and inquiry. For example, when an engineer (operator) of Owner 1 inspects a certain number of rebar in Project 1, a quality report with inspection information and responsibilities must be recorded on the sidechain of Owner 1 (Fig. 9 (a)). The report will be saved as a JavaScript Object Notation file and hashed in the sidechain of Owner 1. The chaincode in the main blockchain will then interact with the backend of the sidechain to check the signature and hash pointer before submitting the hash pointer of the report to the main blockchain. The CFT consensus algorithm enables each entity in the main blockchain to digitally sign the document to reach a consensus, and then the rebar quality report can be committed to the latest block. The inquiry interface in Fig. 9(b) illustrates that by clicking on one of the transactions, the GSU in the main blockchain can track the historical operations of each sidechain and view the block details.



(a) The interface where the Owner 1 submits the rebar quality test report



(b) The interface for the GSU inquiring into the historical operations of the sidechain

Fig. 9. Prototype system interfaces

To sum up, this section has illustrated our dual-layer blockchain-based prototype system developed for construction supervision. The supervision process includes registration, submit-inquire, ordering, and consensus. By illustrating the deployed development environment, backend and frontend prototypes, and user interface, feasibility of the model proposed above is validated because it allows the GSU to monitor the project information of owners while ensuring safety and privacy.

Discussion

The dual-layer blockchain-based model developed in this study provides a structured methodology to enable GSCW. Existing fully decentralized blockchain solutions for construction supervision lack consideration for GSUs, which are unwilling or not expected to give up their centralized status but are still interested in using blockchain. This study draws on China's DCEP system experience to design a blockchain network typology, taking into account the information safety and privacy of owners and the control requirements of the GSUs. The prototype system illustrates implementation of the proposed model in supervising project information in construction.

Compared with existing blockchain solutions for construction supervision, the dual-layer blockchain model has four novel aspects. Firstly, the dual-layer blockchain structure means that no structural changes related to the current status of GSUs are needed. This is advantageous because it is difficult to change existing institutional arrangements in construction. The proposed model can help maintain GSU central governance, enhance project information security and privacy, and improve information-sharing efficiency. Concurrently, compared with the existing multi-layer contract system, the dual-layer blockchain-based model enhances communication and accountability processes. The reason is that the model can send and receive information through fewer levels, and the person who handles the corresponding transactions can be traced more easily. Secondly, the proposed model is scalable and open to extra owners without significantly changing network typology and model configuration. Previous blockchain research only focused on a particular construction process (e.g., production, supply chain, or on-site assembly). In contrast, the model proposed in this study can be extended and applied to the lifecycle and multiple tasks in project delivery. Thirdly, the model provides a valuable reference for designing blockchain governance policies, including relevant regulations, laws, policies, and standards. Policymakers can simulate different arrangements of blockchain network (de)centralization level in the prototype platform. Fourthly, the model is integrated with an incentive mechanism to enhance communication willingness.

DCEP is not immune to criticisms. Although it adopts one-way anonymity, unlike cash and cryptocurrencies, authorized institutions can still trace transactions. If DCEP were used for international business transactions, the surveillance would cause privacy concerns in the global community. The same surveillance controversy also applies to the developed model for GSCW. When transactions are submitted to the main blockchain, the transactions will be hashed, protecting data privacy between participating entities. Nevertheless, it is a challenge to ensure that the supervised and queried information is not intentionally or unintentionally leaked at the top level. Therefore, from a legal perspective, more research on the blockchain network is needed to ensure that the "rule of blockchain" operates within the rule of law. The PBC has a series of considerations regarding technological (e.g., user-perceived benefits), organizational (e.g., top management support), and environmental (e.g., regulatory environment and government support) aspects to help enterprises, ranging from large to small, to adopt DCEP. Similarly, further empirical research is needed to establish strategies to drive the adoption of blockchain by organizations of different sizes.

Data sharing techniques have gradually attracted growing attention as a method of remarkably decreasing repetitive tasks. Nevertheless, there is still an issue to be addressed in the process of data sharing: unwillingness to share. Factors such as trust and the economic utility of data sharing may cause participants to be unwilling to share data. However, few studies in construction have been carried out on data sharing in the context of blockchain. The proposed model uses an incentive mechanism to encourage user participation by paying them rewarding points and exchanging for reputational and financial rewards. Scholars can improve the incentive mechanism adopted and explore other feasible incentive models for data sharing in blockchains. Besides, the proposed blockchain-based GSCW model is a decentralized data infrastructure, thereby not naturally concerting complicated information structures (e.g., Building Information Modeling's semantics and ontologies). Therefore, future studies are encouraged to form logical information structures to allow construction stakeholders to add new and revised data to the model consistently.

Conclusions

Governmental supervision plays an indispensable role in existing construction governance systems. Government supervision units (GSUs), in reality, are reluctant or not supposed to give up their central position in a governance structure. However, they are interested in using blockchain owing to its promise in improving immutability, traceability, and transparency. There appears an incompatibility issue between blockchain technology, famous for its decentralization, and existing governmental supervision of construction work (GSCW) practices. This study attempted to address the incompatibility by finding an appropriate network topology with a proper level of (de)centralization and developing a blockchain-based model for GSCW.

Through a series of research activities, including identifying current problems in GSCW practices, cross-sectoral learning from China's digital currency electronic payment (DCEP) system, and conducting in-house design science research (DSR), we developed a blockchain-based model appropriate for GSCW. The proposed model, which is illustrated in Hyperledger Fabric, has two layers. The lower layer is the sidechain of participating entities (construction project teams), containing private transaction records and copies of the main blockchain. The upper layer is the main blockchain, which includes hash pointers and block information of transaction records. At this layer, the GSUs can supervise construction project owners by requesting project information. With help from smart contracts, interaction between the main and the side blockchains can be realized. The model also integrates a points-based incentive mechanism to enhance participation. The model aims to help GSUs maintain a reliable and effective supervision process by having registration, publish-inquire, ordering services, and consensus mechanisms. This research also provides a deployed development environment, backend and frontend prototypes, and the final user interfaces. Therefore, the developed dual-layer blockchain-based supervision model aims to ensure the authenticity of transactions, increase data privacy, and encourage user participation without affecting the autonomy of the project team and the power of GSU.

The limitations of this study provide chances for further investigation. Firstly, the points-based incentive mechanism is yet to be refined by collecting empirical evidence. Future research can explore feasible blockchain incentive models that can dynamically adjust the incentives to maintain user participation. Secondly, the proposed blockchain-based model has not been extensively validated in actual GSCW practice because the construction industry has not yet formed an environment suitable for blockchain. Thus, GSUs are encouraged to cooperate with universities, research institutions, and construction companies to provide projects for pilot tests. Future research and practice are necessary to evaluate and validate the privacy and scalability of the proposed model. A detailed cost assessment for the initial platform establishment, deployment, storage, ongoing maintenance, and monitoring is also required. Thirdly, at the beginning of a construction project, it is necessary to conduct systematic business process analysis to concert the information structure among various applications (e.g., production, transportation, and on-site assembly). Future research can use the results of business process analysis to build and test applications. Fourthly, the operation data fed to the blockchain is endorsed by consensus-based blockchain oracles. More studies on the different types and reliability of blockchain oracles that bridge the off-chain and cyber-worlds are desired to ensure the authenticity of the information. Fifthly, the proposed model does not naturally concert any complicated information structure so far. Therefore, future investigations can focus on blockchain friendly information structures so that construction stakeholders can consistently add new and revised data to the model.

Data Availability Statement

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

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