A study on protocols of cross-chain data synchronization for permission blockchain for construction management

Rui Zhao [1*], Liupengfei Wu [2], Zhe Chen [3], Maohong Tang [4], Weisheng Lu [5], and Fan Xue [6]

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Abstract: The construction industry is encountering management issues, such as low efficiency, inadequate regulation and enforcement, absence of good coordination and knowledge sharing, and ineffective billing practices. Blockchain is also gaining momentum as a part of the digital transformation in the construction area and response to various challenges. Since various blockchain implementations have different specifications for distributed ledger functionality (e.g., high throughput, scalability), blockchains currently function as independent knowledge islands that cannot access external data or conduct transactions on their own. Such information silos must be bridged to create more stable blockchain applications. This research investigates data synchronization protocols for cross-chain technologies in construction blockchain. It screens the most suitable blockchain frameworks for use in the construction industry to establish a consistent approach to support their application in construction blockchain. Finally, a cross-chain data interaction protocol for blockchain-based supply chain and IFC chain construction is proposed.

[1*] Rui Zhao: Corresponding author, Department of Real Estate and Construction, The University of Hong Kong, China
E-mail: jeremyrui.zhao@connect.hku.hk
[2] Liupengfei Wu: Department of Real Estate and Construction, The University of Hong Kong, China
[3] Zhe Chen: Department of Real Estate and Construction, The University of Hong Kong, China

[4] Maohong Tang: Department of Real Estate and Construction, The University of Hong Kong, China
[5] Weisheng Lu: Department of Real Estate and Construction, The University of Hong Kong, China
[6] Fan Xue: Department of Real Estate and Construction, The University of Hong Kong, China

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1 Introduction

By 2022, global construction investment is expected to hit US$12.4 trillion [1]. Low efficiency is currently cited as a significant cause of failure in the construction industry[2]. In contrast, it is among the most critical sectors for future change. The McKinsey Global Institute estimates a $1.6 trillion global productivity deficit that can be closed by enhancing business efficiency[3]. One of the biggest impediments to the building industry's modernization is its reluctance to accept technical advances in contrast to the achievements seen in the logistics, automobile, and mechanical engineering sectors [4]. The distributed ledger technology (DLT), also known as "blockchain," is thought to have the ability to transform many global markets, including construction.

Blockchain is a distributed database where the data or information is stored with unforgeable, traceable, open and transparent, and collectively maintained. Blockchain is a booming technology that plays a positive role in promoting data sharing, optimizing business processes, reducing operational costs, enhancing collaborative efficiency, and building a trustworthy system that cannot be underestimated. [5]. The core hypothesis of blockchain is establishing a digital distributed consensus, ensuring that data is distributed decentralized across multiple nodes with equal knowledge. No single actor has complete network authority, which increases clarity of operation and improves data protection. Blockchain fundamentally reorganizes current process paths in every enterprise where it is applied, carrying many benefits such as mutual learning, instantaneous data sharing, automatic contract execution, network stability, and increased teamwork by putting a focus on trust and cooperation amongst members [1].

Updating and sharing the Building Information Model (BIM) data is one of the most well-known blockchain technology technologies in the construction industry. BIM is a process used in a multi-dimensional digital model for stakeholders to visualize a construction project[6]. International Alliance for Interoperability (IAI) has introduced a protocol named Industry Foundation Classes (IFC) to share consistent and precise building information between software applications used during the lifecycle of a project or asset. IFC plays a vital role in improving interoperability between software and shunning information loss. As a result, end-users can better cooperate regardless of which applications they use. [7].

BIM model has rapidly become a common forum for all parties to collaborate on a single and collaborative model in the Architecture, Engineering, and Construction (AEC) industry. The BIM maturity level can be used to identify supply chain management problems in BIM [8]. Due to a large amount of variability between the modified design of the BIM model and the supply chain., there is a need to form two separate blockchain networks for the BIM model and the supply chain model to interact with data about the parts of the BIM model. The intelligent contract structure keeps the data in all chains current in real-time, checking and content and part functionality within the model from the design process to the execution phase. A cross-chain protocol is needed to solve the confidence function between various blockchains and realize knowledge transmission between blockchains.

The paper is organized as follows: the next section gives an outlook on the prospect of blockchain technology in the construction industry, introduces the IFC file-based BIM model, and describes the application of blockchain and BIM in the supply chain, followed by a comparison to select the most suitable blockchain framework for the construction industry. Then, the following section describes the whole process of data interaction in the two chains, the IFC chain, and logistics blockchain. The final section concludes and discusses future research needs.

2 Blockchain in construction

2.1 BIM on chain

It is essential to provide compatible resources and assets within the construction industry project, where many companies work intensively on ad hoc variations of specific projects. Widespread and proven frameworks, ideally based on open standards, are essential for the project members to communicate and cooperate without having any special proprietary software. BIM software's advanced technologies enable a shift in the construction industry's use of information technology, going from a static visual representation of a building to an interactive semantic product and process model [7]. Information sharing can be the starting point for using BIM in the phase of design, construction, and operation. Information sharing necessitates creating a computing system in which users will effectively share data independent of software or data place.

IFC can close the divide between stakeholders and project stages in the construction industry's fractured project world. IFC-supported model-based architecture can alter the foundations of the construction process. The potential for productivity gains is enormous: transparent interoperability of building information models would allow for a continuous flow of design, expense, project, manufacturing, and maintenance data, minimizing complexity and increasing reliability during a building's life cycle [9]. As a result, the IFC initiative is one of the most aggressive IT standardization initiatives in any sector.

The hierarchical structure of the IFC data model is divided into four layers: resource layer, the core layer, interop layer, and domain layer. As shown in Figure 1, the resource layer contains the most basic information. Entities within the same structure at each layer can be referenced to each other. They can also be cited by entities of the upper level instead of referenced by entities at the lower level. That is, the quotation of entities must follow the principle of top-down or same-level reference. Based on this principle, the upper layer changes cannot directly interfere with the information of the lower layer, which ensures the stability of the system architecture.

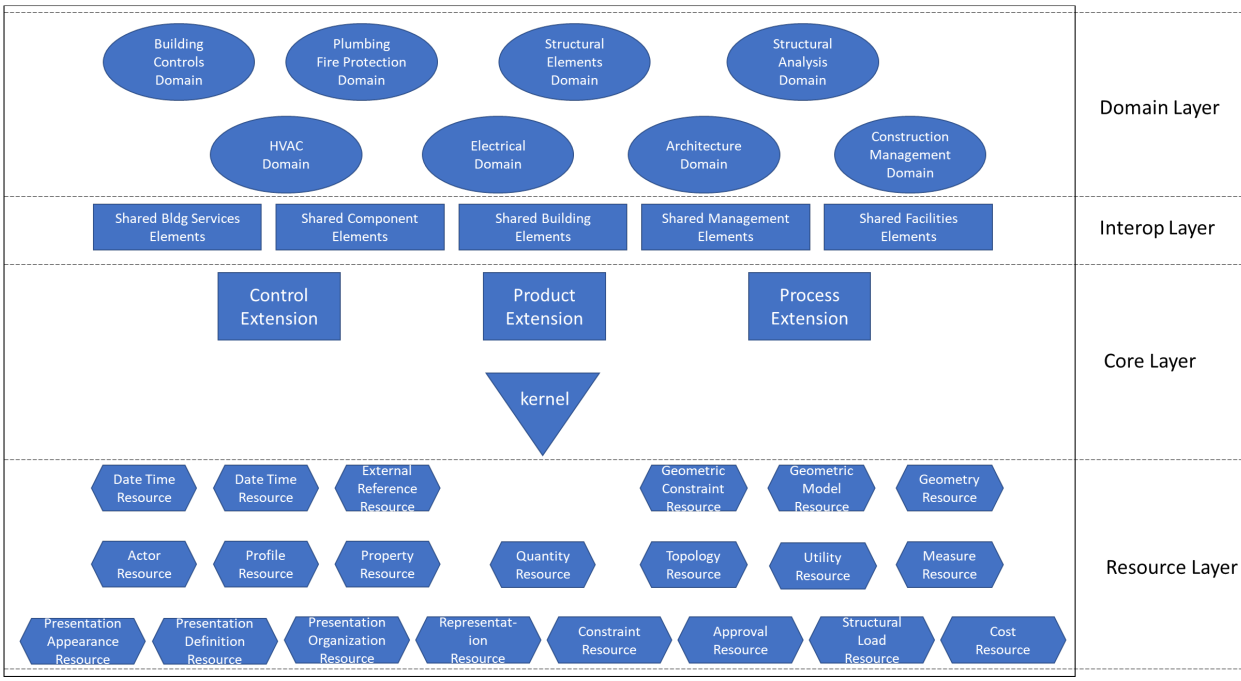

Figure 1. The layers of the IFC data model

Although data storage space and Internet speeds are becoming more affordable, information efficiency and speed must be considered in blockchain BIM models. Due to the high redundancy of IFC files and the characteristics of larger files, Xue and Lu [10] propose a semantic differential transaction method that minimizes the information redundancy of BIM and blockchain integration. Using this approach, one can store the original BIM model in the local terminal and store the IFC altered part of the BIM model into the blockchain instead of the whole IFC file. This approach reduces the redundancy of IFC files in the blockchain. Also, it takes full advantage of the tamper-evident historical data and the traceability of transactions in blockchain technology.

2.2 Supply chain management on chain

Each day, billions of goods are produced globally across diverse supply chains that span the globe. Even though goods move through an extensive network of manufacturers, dealers, transporters, warehousing facilities, and suppliers engaged in the design, processing, delivery, and distribution of goods, these journeys are almost always invisible to us [11]. Supply chains are getting more complicated, extensive, and multinational. End-to-end supply chain transparency and accountability can aid in modeling product flow from raw materials to manufacturing, testing, and finished goods, allowing for new types of organizational, risk, and sustainability analysis. [12].

As a cutting-edge technology, blockchain could bring new changes to supply chain architecture, organizational processes, and day-to-day management. The potential of blockchain to ensure the reliability, traceability, and validity of information and trustless networks built on smart contracts provide a technological reserve for supply chains and supply chain management [13]. In contrast to traditional supply chains, there are four key players unique to blockchain networks that perform critical functions in blockchain-based supply chain Registrars, providing unique identifiers to the network participants. Standards bodies establish system standards for blockchain development strategies and technical specifications, thus enabling the possibility of fair trade. On the other hand, certificates provide certificates of authorization to a segment of the population participating in blockchain-based networks. In addition, the licensed auditor is responsible for auditing the stakeholders who are approved to participate in the network, such as suppliers, distributors, and consumers [14]. The supply chain removes the need for a trustworthy central organization to manage and administer the infrastructure by integrating with blockchain technology, allowing consumers to examine an uninterrupted chain of ownership and purchases from raw materials to final sales. When transactions occur through these various blockchain knowledge dimensions, this information is documented in the ledger and is verifiable [15].

2.3 Comparison of existing blockchain systems

There are currently several blockchain systems available, such as Bitcoin [16], Ethereum, Hyperledger-Fabric, and IOTA. Proof of work (POW), proof of stake (POS), practice byzantine fault resistant (PBFT), and CITA (Tendermint) are examples of mainstream consensus algorithms. We compare the functionality, stability, and applicability of popular blockchain systems and consensus algorithms in construction scenarios. Li, Greenwood [17] analyzed the difficulties and prospects of blockchain applications in the construction industry. They argue that one of the challenges is that the BIM models are too large, and the transactions are too concurrent. However, simultaneously, blockchain applications will enable the industry to manage resources better and reduce costs, project schedules, and payment disputes. We identified four conditions for a blockchain framework appropriate for the IoT scenario based on previous studies and our Summary, including the ability to include heterogeneous networks, consensus algorithms based on BFT, no transaction costs, and scalability.

First and foremost, blockchain technology can support a diverse network. When designing a blockchain network for the construction industry, a heterogeneous network with several sub-networks to manage a range of business logic is needed.

Secondly, we assume that for construction blockchain scenarios, blockchain networks with higher latency, greater scalability, and no transaction fees are more appropriate. Fast transaction validation is a critical criterion for building blockchains, which necessitates blockchains reaching consensus without forking. This condition can only be met by using the BFT-based consensus algorithm. Furthermore, since mature construction blockchain networks must process a vast number of transactions every day, transaction fees would place unacceptably high costs on customers, which is well addressed by Hyperledger Fabric's zero transaction fee function.

The third requirement is that the blockchain framework is scalable. Higher performance and scalability criteria are enforced on the infrastructure for a building blockchain, such as a large number of participants, a large volume of transactions, a large volume of records, or a substantial rise in the number of users, and a single-chain implementation would often face issues with software architecture or hardware resources. According to the blockchain's framework characteristics, attacking nodes on the blockchain will improve the system's fault tolerance and the energy spent in credit endorsement of participants without enhancing efficiency.

A comparison of some significant blockchain networks is shown in Table 1. A thorough analysis reveals that no one blockchain will satisfy the whole construction blockchain scenario requirements. Therefore, a federated chain such as Fabric, which is different from the Bitcoin mechanism and targeted for industry use, is better suited for architectural blockchain environments.

Table 1. Comparison of blockchain systems[18]

Features	Bitcoin	Ethereum	Hyperledger-Fabric	CITA
Consensus	POW	POW, POS	PBFT	BFT
Consensus finality	×	×	✓	×
Blockchain forks	✓	✓	×	✓

Smart contracts operability	×	✓	✓	×
Fee less	×	×	✓	×
Scalable	×	×	×	✓
TX throughput	8 TPS	9-10 TPS	Thousands of TPS	8-11 TPS

3 Cross-chain for blockchain-based supply chain and BIM chain

3.1 Cross-chain technology for the construction industry

Blockchain is a comparatively closed framework as compared to conventional database-based data storage. At the moment, the majority of blockchain-based protection implementation scenarios use separate blockchain networks that are separated from one another and challenging to interconnect and horizontally expand, impeding the efficient transmission and circulation of digital assets across systems. With the success of blockchain implementations and their features' sophistication, further cross-chain standards are being proposed [19]. Remote verification and cross-chain authentication data interoperability are essential in the building field due to the generally broad number of players participating in the same project where the authentication standards span different security domains in heterogeneous blockchain networks [10]. However, there are very few cross-chain technology multi-domain authentication solutions.

Notary systems, side chains/relays, and hash locking are the three processes that make up cross-chain technology. Various cross-chain solutions are appropriate for multiple implementation situations. The side chain and relay chain are the preferred cross-chain technologies for multi-domain authentication in the construction industry [20]. Lightweight client-side authentication is possible with this technology. It assesses the validity of a given authentication case and state in the cross-chain scheme using smart contracts to verify the validity of a cryptographic hash tree.

The open web blockchain network is distributed, and its access protection is critical in the construction industry. Conventional authentication of access is focused on PKI in a centralized scheme[21]. The majority of the current multi-domain authentication is for large-scale networks of the same kind and rarely includes domain authentication of heterogeneous systems. Existing inter-domain authentication schemes challenge satisfactory authentication results, particularly for blockchain users on various blockchain platforms. Therefore, we develop the PBFT process based on cross-chain technologies and provide a multi-domain data system synchronization protocol suitable for blockchain construction to tackle security issues in building blockchain authentication [22].

3.2 Authentication scenario

The construction blockchain's endpoints are separated into several domains in this case, with each domain named after its stored contents. The BIM model domain's blockchain, responsible for storing the IFC information in the BIM model, is called the IFC chain. It holds the domain's local authentication information and a federated blockchain called SC chain, which contains each domain's local authentication data metadata. If cross-domain authentication is required, the authenticator may read the federated chain's metadata to verify the access rights of the authenticated endpoint.

The scenario of the interaction between the IFC chain and the blockchain chain for supply chain (SC chain) of the BIM model of interest in this paper is shown in Figure 2. The upper part is the IFC chain responsible for maintaining the local authentication blockchain, which has multiple endpoints in the domain corresponding to BIM clients, customers, architects, building structure designers, building service designers, and other professionals. The below part is the SC chain, which exists as a federated chain, where all relevant stakeholders in the supply chain system can implement and view the BIM models on the chain.

Overall, cross-chain transactions require the completion of four steps: authentication, consensus, packaging, and block storage. The local blockchain first authenticates the identity of the requester if cross-domain interaction is needed. Following verification, information for local authentication is shared via cross-chain technology to the federated chain. The requesting node's authentication is completed on the public authentication blockchain using the PBFT-based authentication policy and the distributed authentication algorithm. After the authentication is transmitted, cross-chain technologies collect and exchange authentication information into the local chains of the other domain to obtain authentication certificates; for more information on the authentication method, see below.

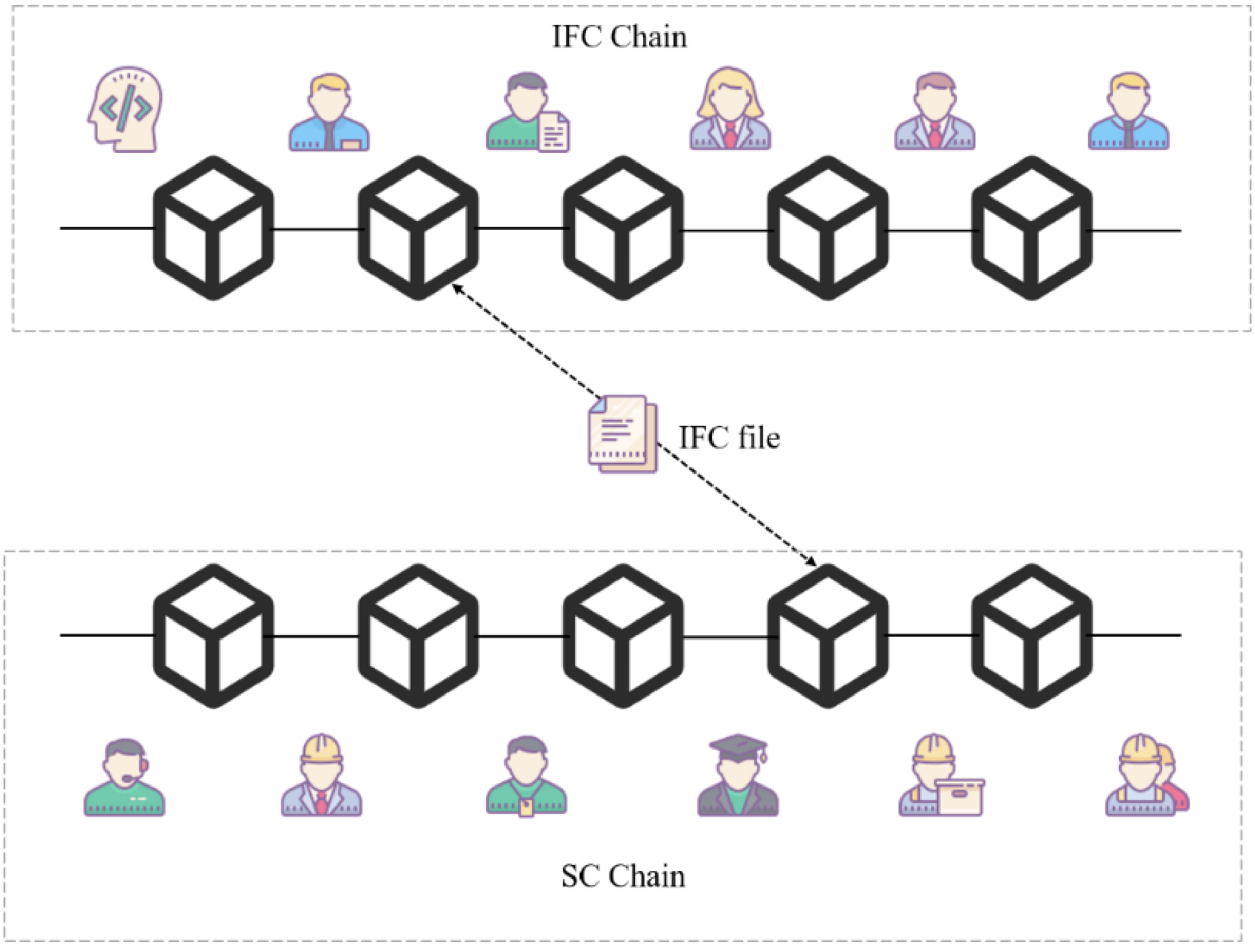

Figure 2. The possible authentication scenario

3.3 Cross-chain data exchange

The side-chain of cross-chain technologies is used to migrate data between the local and federated chains. A side-chain is a protocol that enables tokens to switch properties between blockchains securely. Thanks to two-way pegging technologies, the main chain's infrastructure can be operated to some extent after the connection. Digital objects can be securely moved from the first blockchain to the second blockchain using side-chain technology and then safely restored from the second blockchain to the first blockchain at a later period [23]. The first blockchain is known as the main chain, and the second blockchain is known as the side chain. From the single chain of the main chain, the side chain can virtually enhance the main chain's performance horizontally and vertically. Through the side chains, the main chain looks like it supports these functions as well. By virtualization, it means that although there are horizontal and vertical enhancements, the main chain itself does not have any changes. Still, only the many side chains help it play a proxy-like role to make it look like the performance is improved [24].

Via two-way anchoring technology, the side-chain implementation understands cooperation and data exchange between the master and slave chains. When a master chain asset is secured, the side-chain asset that corresponds to it may be opened. When the side chain's assets are closed, the master chain's equivalent assets are opened. The most significant challenge in introducing bi-directional anchoring is that the protocol change must be consistent with the current main chain, i.e., it must not interfere with the main chain's functionality. The specific implementation methods are the single hosting model, federation model, SPV model, drive chain model, and hybrid model[25].

1)Single Hosting Mode: when the main chain's side chain is synchronized, a trustee is appointed to perform information locking, asset synchronization, and unlocking tasks.

2) Federation Model: the other name is the notary model, in which multiple signatures from multiple notaries sign off on transactions that transfer assets, avoiding centralization.

3)SPV Mode: By sending a transaction to a particular address on this chain, an SPV certificate is automatically created to the side-chain, and a transaction is initiated to unlock the corresponding asset on the side-chain

4)Drive Chain Model: The Drive Chain model uses miners as the custodian of funds and issues custody of assets to digital asset miners, who vote on when to unlock the assets and where to send them.

5)Hybrid Model: The hybrid model is an effective combination of these side-chain mechanisms, using the most suitable model for chains with different structures, such as SPV for the main chain and drive chain for the side chains.

3.4 Data structure

A block is a storage system for storing ledger data. The unforgeable cross-domain certification certificates in the block can be checked publicly after encryption with public and private keys. The block data structure defines the authentication certificates' description specification, security policies, and security level in the cross-chain authentication information sharing: the header and data parts of the cross-domain authentication block [26]. Four terms make up the header: (1) the previous block's data and the parent block's hash index; (2) a timestamp to record the transaction time; (3) Nonce (random number, counter for workload proof algorithm); and (4) Merkle tree root data that summarizes and quickly summarizes all the transaction data in the checksum block. Figure 3 illustrates the structure of the data. A Merkle tree is essentially a tree-like data structure consisting of data blocks, leaf nodes, intermediate nodes, and root nodes. The hashing operation used to generate the Merkle tree is a standard cryptographic function in the blockchain. Data of arbitrary size and length are hashed to obtain a fixed size and length value, i.e., the hash value. The certificate content includes the certificate version number, serial number, certificate signature algorithm, message-digest algorithm, and other generation information. The validation information for cross-domain authentication is stored in the Merkle tree of the blockchain by nodes in the alliance chain [27].

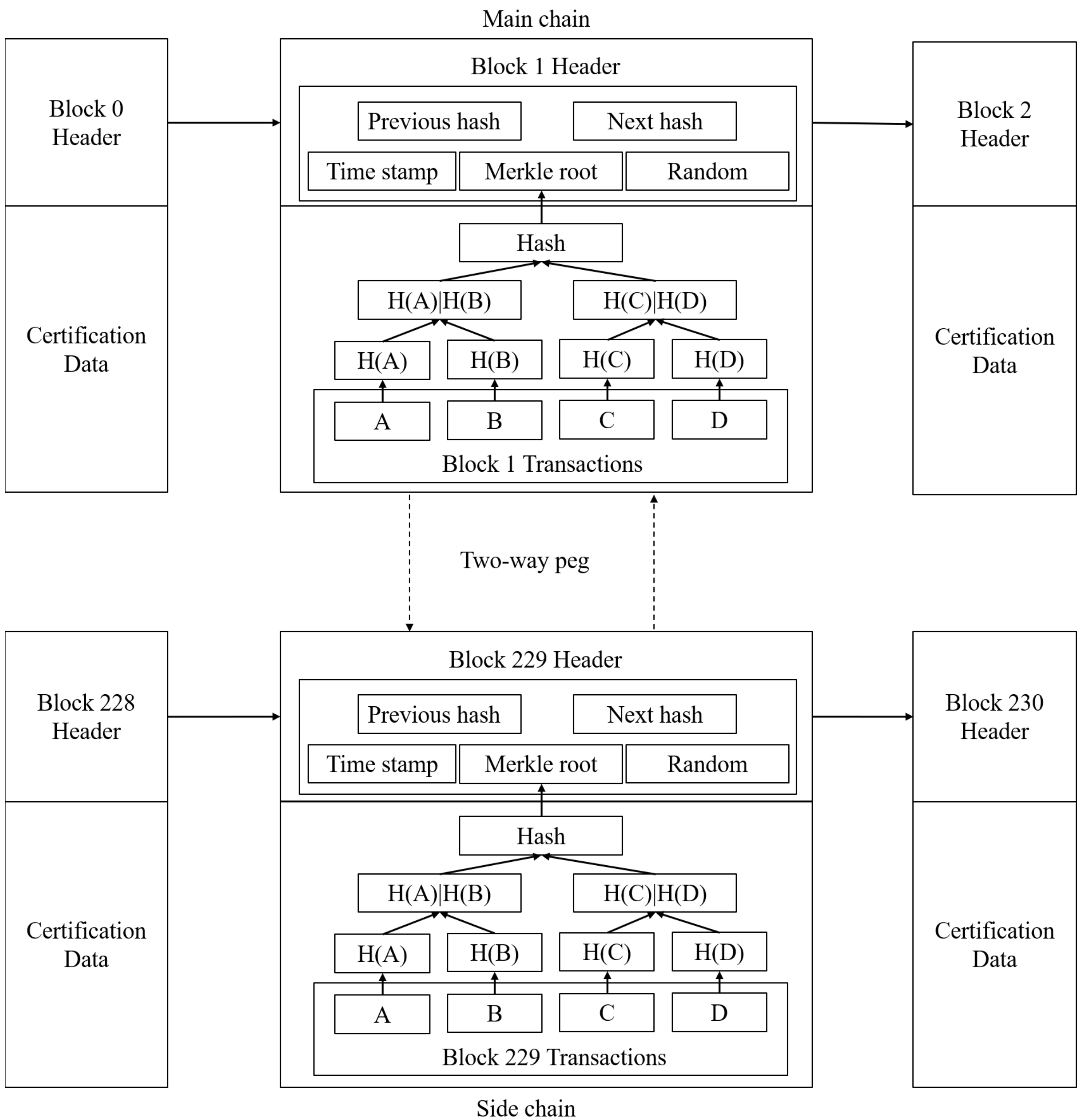

Figure 3. The structure of the certified blockchain

3.5 Certification process

Figure 4 depicts the cross-domain authentication method, which involves registration, authentication order, token transfer, distributed authentication, and authentication passing.

3.5.1 Register

In the registration phase, terminal A in the IFC chain initiates registration based on a unique ID and triggers the digital signature and encryption mechanism on the local chain. The system generates and returns the public key encrypted registration information Sign(UUID||timestamp||n1) of the terminal through the certificate of the terminal, where n1 is a random number selected by the system. Through the above operation, the IFC file completes the registration process.

3.5.2 Authentication

When the terminal on the IFC chain needs to access the resources on the SC chain, the terminal initiates the authentication request Request(IDIFC||PubIFC||timestamp‖businuss_code), which includes the IFC file ID where the transition happened, the transaction's public key, and the company form. Following validation by the local chain, it establishes a two-way link with the authentication SC chain. It synchronously transmits the IFC chain's authentication request information and the certificate information to the relay chain, resulting in the relay chain having both the IFC chain's authentication certificate and the cross-domain authentication request of this terminal.

3.5.3 Verification

The relay chain's smart contract will conduct distributed authentication of the nodes applying for entry. The authentication group is formed by selecting nodes from the relay chain that satisfy the threshold number. For distributed authentication, the PBFT consensus algorithm is used. Finally, the relay chain stores the authentication data. The authentication result is stored in the relay chain's distributed ledger after a smart contract is triggered, after which the relay chain will transfer the authentication credential information to the SC chain's blockchain through a two-way hook, allowing the SC chain's nodes to authenticate the terminals on the IFC chain.

Finally, the IFC chain node verified by the SC chain terminal will obtain the timestamp of the IFC file on the SC chain and use the smart contract to compare it with the timestamp when the transaction was submitted. If the timestamp on the SC chain shows a time later than when the IFC chain introduced the transaction, it proves that a change in the IFC file on the Sc chain that was not requested by the IFC chain occurred after the transaction was submitted. Then the transaction is considered to be risky, and it is recommended to proceed later, although the probability of this happening in the construction field is small.

3.5.4 Connection creation

After the IFC chain's terminal sends a remote access request to the SC chain's terminal, the SC chain's terminal authenticates the request before invoking the SC chain's smart contract to check the access request. Since the terminal on the IFC chain has contact authority on the SC chain, the terminal on the SC chain will quickly validate the identity and authority of the terminal on the IFC chain, and safe communication can be developed after authentication, thanks to the distributed consensus of the blockchain and the security property of unforgeability.

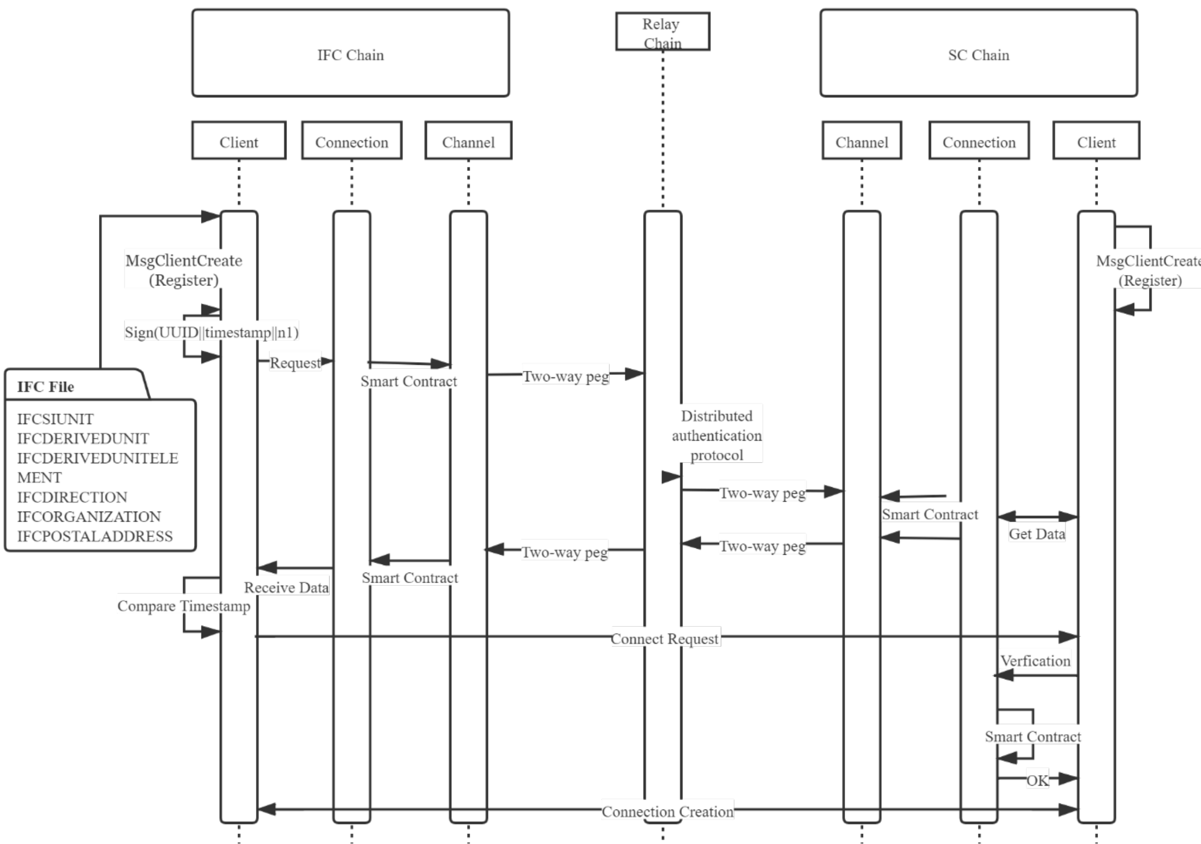

Figure 4. Access authentication process

4 Summary

This paper focuses on the cross-chain technology research of blockchain in the construction field. In the construction field, the vast BIM will bring tremendous network transmission pressure. The data cannot be processed in parallel, bringing more significant trouble for the stakeholders involved in the construction process. To solve the problem, we analyzed a variety of blockchain models with broader circulation. We compare and filter out the most timely coalition chain used in the construction field, propose the collapse strategy using two-way anchoring, and finally propose an improved network communication protocol. This study can lay the initial foundation for cross-chain research in the construction field and pave the way for the subsequent technical improvement of cross-chain protocols for blockchains specifically used in the construction field.

Future works are suggested in the following directions. First, a docker cluster is built using Kubernetes to join a large amount of actual data for multiple batches of experiments and compare with various cross-chain technologies popular nowadays. Second, a blockchain model based on this cross-chain protocol and combined with a distributed machine learning paradigm called federation learning is used to build efficient machine learning models among multiple participants or multiple computational nodes to solve the pervasive information silo problem.

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