Research on multi-person collaborative design of BIM drawing based on blockchain

Jinlong Wang, Yumin Shen, Xiaoyun Xiong, Xu Wang & Xiaoxue Fang

The existing multi-person collaborative design scheme of Building Information Modeling (BIM) integrated with blockchain faces problems such as poor reliability of BIM drawing, inconsistent drawing information, redundant information, and inaccurate protection of copyright interests. This paper proposes a multi-person collaborative design model for BIM drawing that combines blockchain and InterPlanetary File System (IPFS). This model uses blockchain to store drawing design information to protect the copyright interests of designers and combines IPFS to ensure the reliability of drawing. A cycle division mechanism is designed to solve the problem of drawing information synchronization when multiple people collaborate in design. The Semantic Differential Transaction (SDT) method is used to achieve incremental update of drawing and reduce the information redundancy of the blockchain. Finally, a comparative analysis and validation evaluation of the scheme is carried out, and the usability of the scheme is illustrated with an illustrative example. The results show that: (1) proposed scheme is feasible for multi-person collaborative design; (2) proposed scheme can effectively ensure the reliability of drawing and reduce the redundancy of blockchain information, so as to achieve copyright protection for designers.

Currently, Building Information Modeling (BIM) is gradually being used in the design, construction, and maintenance of large-scale buildings. Due to the complexity of large-scale construction projects, multiple disciplines such as architecture, structure, and equipment are usually involved in the design, and the workload is large. In order to improve efficiency, BIM multi-person collaborative design is currently mainly based on cloud platforms or the collaborative design function of modeling software. Cloud-based BIM collaborative design (e.g., Autodesk BIM 360, BIMServer) uses the cloud to store and manage BIM drawing data. Although cloud storage has the advantages of high flexibility and strong scalability, due to the influence of centralized management, data security problems such as data loss, tampering and sensitive data leakage are prone to occur. The collaborative design function of BIM modeling software such as Revit has higher requirements on network speed and hardware performance, and it is difficult to effectively record the copyright information of BIM drawing and protect the copyright interests of BIM designers. In addition, both of these methods need to be based on trusted third-party services to realize the storage and update of BIM drawing collaborative design results, which is difficult to ensure the safety and reliability of multi-person collaborative design data.

Blockchain is a distributed ledger with features such as decentralization, traceability, and tamper resistance. It has been successfully applied to IoT systems, Industry 4.0, and electronic medical records. Due to its characteristics of secure data storage and reliable sharing, blockchain technology has been gradually applied to BIM drawing design. Reference proposed an innovative construction project management model that integrated BIM and blockchain to provide new ideas for digital construction and collaborative management of construction projects throughout their life cycle. Kasten systematically reviewed and summarized the relevant literature on the application of blockchain in BIM and put forward suggestions for further research directions. All the above studies mentioned the application of blockchain to multi-person collaborative design of BIM drawing. Although these studies did not discuss the design or process of related schemes in detail, they provide directions and goals for subsequent research. Reference used blockchain to record operation information such as uploading, downloading and deleting of BIM drawing in rail transit projects, which ensured the flow of files and the traceability of responsibilities between multiple parties. Tao et al. used BIM Collaboration Format (BCF) to complete multi-person collaborative design operations on BIM drawing, and used blockchain and InterPlanetary File System (IPFS) to store BCF file generation information and corresponding BCF files, which improved the security and reliability of design data. Shen et al. proposed a multi-person collaborative creation...
A multi-person collaborative design model of BIM drawing based on blockchain is proposed. Besides, prototype system is implemented according to the proposed model, which can provide a complete function for multi-person collaborative design of BIM drawing.

The collaborative storage method based on blockchain (on-chain) and IPFS (off-chain) is adopted, which solves the problem that blockchain cannot store large data such as BIM drawing file. To protect the copyright interests of designers, IPFS is used to ensure the integrity and reliability of BIM drawing.

A cycle division mechanism is designed to solve the problem of information synchronization during multi-person collaborative design of BIM drawing, which can ensure the consistency of BIM drawing.

Incremental update of BIM drawing is realized using SDT method, which reduces the information redundancy of BIM.

The developed system is thoroughly tested through the following aspects: time-consuming of BIM drawing collaborative design, transaction throughput, and BIM drawing consistency. In addition, security and reliability of developed system are also analyzed. Finally, the usability of proposed scheme is verified by an example.

The rest of this paper is arranged as follows: section “Related work” summarizes the literature on integrated application of BIM, blockchain and architecture. Section “Multi-person collaborative design model of BIM drawing” is to propose a multi-person collaborative design model of BIM drawing based on blockchain. Section “Detailed structure and process design of BIM drawing multi-person collaborative design model” is to expound the detailed structure of proposed model and related processes. Section “Experimental verification and evaluation analysis” implements the prototype system, and designs experiments to test and evaluate the relevant indicators and functional processes of this system. Finally, section “Conclusion” concludes the whole paper.

Related work

Traditional BIM drawing multi-person collaborative design. Currently, BIM multi-person collaborative design tools or platforms used in large-scale construction projects are mainly divided into two categories: (1) single tools that promote data exchangeability and interoperability, and (2) integrated BIM-based collaborative design platforms that facilitate comprehensive collaboration. The first category of tools facilitates collaborative design by enhancing a specific aspect of BIM data, such as recording BIM design changes, enhancing compatibility of BIM data formats, or version management of BIM data. However, these studies have problems such as low data access and sharing efficiency, and large application limitations. In contrast, the second type of multi-person collaborative design platform does not have the above problems, and it can provide more abundant and practical functions for BIM multi-person collaborative design. Moayeri et al. proposed a new visualization model, which visualized the changes and modifications of BIM in construction projects. El-Diraby et al. used related plugins to combine the BIM online design platform with energy simulation software, and ultimately helped people make decisions about “green buildings” through comprehensively considering design and simulation results. Poerschke et al. conducted research on BIM data collection, analysis and information collaboration. They proposed the methods design collaboration and design presentation between different disciplines in the stage of architectural design. Singh et al. studied the multi-professional collaboration in the U.S. construction industry, analyzed the problems during the process of data interaction between different disciplines, and proposed a collaboration platform based on BIM server according to the relevant analysis conclusions. Liu et al. introduced a cloud-based BIM data center, which provided functions such as storage, sharing, and retrieval of BIM-related data. Logothetis et al. proposed a cloud-based open-source system for storing, viewing and analyzing BIM-related data online.

The tradition studies often store BIM data in the cloud or database for sharing, so as to assist the real-time collaborative design of BIM. These studies improve the understanding of design information in the BIM multi-person collaborative design process and provide practical solutions to facilitate multi-person collaborative design. However, there are still some problems in these schemes, such as the inability to guarantee the security of collaborative data, the confusion of BIM drawing version management, and the redundancy of information, which need further research and improvement.

Blockchain in construction. Blockchain technology enables highly reliable and traceable data management based on distributed ledgers and consensus mechanisms. Each block in the blockchain has two hash values, “current block hash” and “previous block hash”. The latter block is linked to the previous block by “previous
block hash", and finally a chain is formed. Any slight modification to block information will cause the block hash to change. Therefore, if someone tries to tamper with a block in their local blockchain ledger, the block will be recognized by other blockchain nodes because of the hash mismatch. Not only that, no single blockchain node can manipulate all the data in the blockchain. Because only when a malicious blockchain node holds more than 50% of the computing power, it is possible to control the entire blockchain network, which is almost impossible from the current technical point of view. Therefore, blockchain can guarantee the security and trustworthiness of data by keeping the same, unalterable and traceable copy of complete data in each node.

In recent years, the application of blockchain in the construction field has been increasing, and it has played an important role in driving the digital transformation in construction field, reducing costs, accelerating collaboration and maximizing trust. For example, Wen et al. proposed a blockchain-enhanced price-incentivized demand response framework for demand-side management, enabling optimal energy scheduling among multiple users within a building. Van et al. proposed a blockchain-based distributed cooperative energy response framework for managing the use of renewable energy by users in buildings. Das et al. proposed a distributed building construction document management system based on blockchain and distributed content addressable storage, which promoted the smooth flow of construction information among different project participants and improved the quality of construction projects. Wang et al. proposed a blockchain-based framework for enhancing supply chain traceability in off-site construction. Lee et al. proposed a framework combining blockchain and digital twins to track data records in construction projects. Das et al. developed a blockchain-based construction project payment framework, utilized smart contracts to automate payments and share payment records among all members. Li et al. applied blockchain to the buildings internet of things system to improve the sustainability of construction projects and the reusability of data. Sheng et al. designed a construction quality chain based on blockchain to ensure the security of construction quality information and enhance the trust among construction project members. Zheng et al. used the blockchain to record the whole process design information of BIM, which ensured the security and traceability of design information. Liu et al. explored the potential role of the integration of BIM and blockchain for sustainable building design information management, and used blockchain to assist BIM for sustainable building design coordination and collaboration across multiple construction stages. Lokshina et al. studied the integrated application of blockchain, BIM and buildings internet of things system. They proposed that the integrated application of these three can provide an innovative framework for digital transformation of construction industry. Nawari et al. investigated the potential integration of blockchain and BIM processes by conducting a survey of blockchain and its application in a built environment. Li et al. focused on digital transformation of construction industry, reviewed current technology, environment, conceptual models, and discussed the application and development trend of blockchain technology in digital construction.

In summary, blockchain has attracted extensive attention in the construction field due to its potential in many aspects such as data security, data traceability, identity authentication, access control, and traceability management of BIM and supply chains. Blockchain can record and save the complete modification and change history of BIM, which has great potential in the field of building safer digital buildings. Therefore, safe, precise and efficient management during the digital process of construction projects depend on the effective integration and support of blockchain and BIM.

### Multi-person collaborative design of BIM drawing based on blockchain

In view of the situation that large-scale construction projects often involve multiple parties, blockchain is gradually used to solve the problems of multi-party trust and security traceability in BIM design. Winfield pointed out in the report that blockchain can provide synchronized, tamper-proof and traceable data records, showing great potential to solve the problem of BIM collaborative design. Elghaish et al. asserted that the organic integration of blockchain and BIM can easily track all BIM changes in design and construction phases of the building project. Nawari et al. believed that blockchain can play an advantage in BIM collaborative workflow by providing secure and reliable data storage. Li et al. used blockchain to protect intellectual property, data ownership and copyright in BIM collaborative design. Zheng et al. proposed using blockchain to record the changes of BIM drawing during the collaborative design process, thereby ensuring the credibility and security of the design process. Most of the current researches combining blockchain and BIM multi-person collaborative design are conceptual frameworks, which are given and compared in Table 1.

### Table 1. Research on the combination of blockchain and BIM multi-person collaborative design.

| References          | Data storage | On-chain data                                      | Off-chain data        | Consolidated storage | Consistency | Information redundancy |
|---------------------|--------------|---------------------------------------------------|-----------------------|-----------------------|-------------|-----------------------|
| Wang et al.         | Mixed        | BIM design content                                 | IPFS                   | Yes                   | Yes         | No                    |
| Duan et al.         | Blockchain   | BIM complete information                           | /                      | No                    | No          | Yes                   |
| Tao et al.          | Mixed        | summary of BIM design operation information        | IPFS                   | No                    | No          | Yes                   |
| Shen et al.         | Mixed        | summary of BIM complete information                | Database               | Yes                   | Yes         | Yes                   |
| Das et al.          | Mixed        | BIM design content                                 | Database               | No                    | No          | Yes                   |
| Xue et al.          | Blockchain   | BIM design content                                 | /                      | No                    | No          | No                    |
From the perspective of data storage methods, there are mainly two methods: blockchain storage and hybrid storage. Among them, blockchain storage can ensure the safety and reliability of data on the chain. However, due to block size and other reasons, blockchain is not suitable for storing large files such as BIM drawing and cannot protect BIM drawing files and BIM drawing change information at the same time. Literature25 tried to use blockchain to store the complete information of BIM drawing, but it would bring serious information redundancy problems23. Compared with blockchain storage, hybrid storage is more flexible and efficient. The basic mode is to use blockchain to store brief abstracts or design information, and to store BIM drawing files in off-chain. The difference lies in the choice of off-chain storage methods. Shen et al.23 and Das et al.24 used traditional databases as off-chain storage methods, which faces security risks such as data tampering and leakage56. In response to this problem, literature22 introduced IPFS, a new distributed file storage protocol, to ensure the authenticity and credibility of stored files through operations such as partitioning and encryption. It has great potential to solve the problem of inefficient and huge data storage in blockchain27,37.

From the perspective of data storage content in blockchain (on-chain), literatures21,37,39 and 22 used blockchain to store the complete information of BIM drawing or the summary of BIM drawing design operation records, which has encountered two problems. On the one hand, the complete information of BIM drawing is relatively large, and a large part of it is design-independent which does not need to be stored. Using blockchain to store it will take up lots of storage space. In addition, due to data synchronization between blockchain nodes, information redundancy in blockchain is further increased. On the other hand, the summary of BIM drawing design operation information cannot provide accurate design content, so it cannot be used as a valid copyright proof. In contrast, literature37 utilized blockchain to store accurate design content, and literature39 further proposed the SDT method to minimize the design content that needs to be stored and reduces information redundancy in blockchain.

From the perspective of design process, two issues are mainly considered: (1) how to deal with conflicts between BIM drawing versions and (2) how to ensure the consistency of BIM drawing. As shown in Table 1, only the literature23 considered these two issues. It added version number information for each design and implemented merged storage according to the version number when a conflict occurred. Besides, all designers were required to re-obtain the latest BIM drawing at the beginning of each round of design to ensure the ultimate consistency of BIM drawing. However, there are still some problems such as low efficiency and large storage space needed to be solved in this scheme.

This section compares and analyzes the existing researches on the combination of blockchain and BIM multi-person collaborative design from the perspectives of data storage methods, data storage content in blockchain, and design processes. It can be seen from the analysis results that each scheme has advantages and disadvantages, and there are still some problems to be solved urgently. This paper will give feasible solutions to these problems.

### Multi-person collaborative design model of BIM drawing

Aiming at the current issues of security, consistency, redundancy and copyright in the multi-person collaborative design of BIM drawing, this paper studies the multi-person collaborative design of BIM drawing based on blockchain, and mainly solves the following problems in the traditional multi-person collaborative design of BIM drawing:

1. Aiming at the problem of data security and lack of trust, the on-chain and off-chain collaborative storage method of blockchain and IPFS is adopted. Mutual trust and supervision among BIM drawing designers are achieved through the consensus mechanism to improve data reliability. Meanwhile, the security of the data can be ensured through the anti-tampering feature of blockchain.

2. Aiming at the problem of information fusion and consistency, the cycle division mechanism is used to avoid the problem of information synchronization during design and ensure the consistency of BIM drawing among designers.

3. For the problem of BIM drawing information redundancy and copyright, the SDT method is used to achieve incremental updates of BIM drawing, and the blockchain information records are used to provide reliable copyright proofs to safeguard the designer's copyright interests.

In order to facilitate the following discussion, unified data description is defined in Table 2.

#### Logical framework.

The logical framework of multi-person collaborative design of BIM drawing based on blockchain is shown in Fig. 1. The model is implemented based on Hyperledger Fabric due to the excellent performance and high security which can meet the needs of actual scenarios. The main roles in this model include: Hyperledger Fabric certificate authority (CA), Hyperledger Fabric consortium blockchain (BC), InterPlanetary File System (IPFS), BIM drawing owner (BIM_O) and BIM drawing designer (BIM_D).

The specific tasks of each role are shown in Table 3:

#### Cycle division mechanism.

During the multi-person collaborative design of BIM drawing, in order to ensure the information synchronization among designers and improve the design efficiency, the entire process of multi-person collaborative design is divided into three cycles: drawing review and upload cycle, drawing design cycle and drawing design information fusion cycle. As shown in Fig. 2, the cycle division process is illustrated by adding a window to BIM drawing as an example. A specific role performs the specific operation in each cycle, and each operation is not performed across cycles. The specific divisions are as follows:
### Table 2. Formal description of stored content.

| Symbol | Description |
|--------|-------------|
| AddrIPFS | Hash storage address of BIM drawing in IPFS |
| $D_i$ | BIM drawing, $D_{init}$, $D_{new}$, $D_{update}$ respectively indicate the initial, newest, and updated BIM drawing |
| DAI_record | BIM drawing summary record |
| DAI_Cj | BIM drawing summary related smart contracts, $DAI_{upload}$, $DAI_{download}$ respectively indicate BIM drawing summary upload and download smart contract |
| DDI | BIM drawing design information |
| DDI_record | BIM drawing design information record |
| DDI_Ck | BIM drawing design information related smart contracts, $DDI_{upload}$, $DDI_{download}$ respectively indicate BIM drawing design information upload and download smart contract |
| DFDI | BIM drawing fusion design information |
| DFDI_record | BIM drawing fusion design information record |
| DFDI_Cm | The merged BIM drawing design information related smart contracts, $DFDI_{upload}$, $DFDI_{download}$ respectively indicate the merged BIM drawing design information upload and download smart contract |
| $H_n$ | Hash value, $H_D$, $H_{DDI}$, $H_{DFDI}$ respectively indicate the hash value of BIM drawing content, $DDI$ and $DFDI$ |
| Sigp | Digital signature, $Sig_H$, $Sig_{DDI}$, $Sig_{DFDI}$ respectively indicate the digital signature of $H_D$ and $H_{DDI}$ |

---

**Figure 1.** The logical framework of multi-person collaborative design of BIM drawing based on blockchain.
1. Drawing review and upload cycle: BIM_O performs operations, including BIM drawing update, BIM drawing upload and DFDI acquisition operation implemented through smart contract.

2. Drawing design cycle: BIM_D performs operations, including BIM drawing acquisition, BIM drawing design and DDI calculation and upload operation implemented through smart contract.

3. Drawing design information fusion cycle: BC automatically calls smart contract to execute operations of DDI fusion and upload after each BIM_D uploads DDI to BC. Each cycle is independent, and conversion between cycles is achieved through the change of system status bit. When the drawing status is 'updateable and uploadable', enter the drawing review and upload cycle; when the status is 'designable', enter the drawing design cycle; when the status is 'fusionable', enter the drawing design information fusion cycle. Based on cycle division mechanism, all BIM_D obtain the latest BIM drawing uploaded by BIM_O from the IPFS at the beginning of the drawing design cycle, and then design the BIM drawing. This enables BIM_D to design on the same latest BIM drawing, which ensures the information synchronization when multiple people are designing.

Information storage. This paper combines BC and IPFS to implement the on-chain (BC) plus off-chain (IPFS) hybrid storage of data. Off-chain (IPFS) stores BIM drawing, while the main content stored in BC is shown in Fig. 3.

Different roles upload different BIM data to blockchain in different cycles. An example of BIM data storage content changes on the BC is shown in Fig. 4. Three types of data are uploaded to BC by three roles in three cycles: (1) drawing review and upload cycle, the original data of BIM drawing file is obtained through hash operation by BIM_O, and the BIM drawing summary is generated and uploaded to BC; (2) drawing design cycle, BIM_D uses SDT method to calculate the original data of BIM drawing file to obtain DDI, generates DDI_record and uploads Table 3. The specific tasks of each role within the logical framework.

| Role   | Specific tasks                                      |
|--------|----------------------------------------------------|
| CA     | Generating public/private key pairs for BIM_O and BIM_D |
| BC     | Integrating DDI to generate DFDI, storing data (e.g., DDI_record, DFDI_record, DAI_record, etc.) and performing data encryption, signature and verification |
| IPFS   | Storing complete BIM drawing                      |
| BIM_O  | Updating and uploading BIM drawing according to DFDI |
| BIM_D  | Acquiring and designing BIM drawing, then uploading them after calculating DDI |

Figure 2. Example of cycle division and circulation.

- 1. Drawing review and upload cycle: BIM_O performs operations, including BIM drawing update, BIM drawing upload and DFDI acquisition operation implemented through smart contract.
- 2. Drawing design cycle: BIM_D performs operations, including BIM drawing acquisition, BIM drawing design and DDI calculation and upload operation implemented through smart contract.
- 3. Drawing design information fusion cycle: BC automatically calls smart contract to execute operations of DDI fusion and upload after each BIM_D uploads DDI to BC.
it to BC; (3) drawing design information fusion cycle, smart contract deployed in BC automatically uses SDT method to fuse each DDI to obtain DFDI, generates DFDI record and uploads it to BC.

**Running process.** As shown in Fig. 5, the running process of model includes the following steps:

**Step 1:** Global configuration. It is executed by CA. The public and private key pairs are automatically generated when a new BIM-O or BIM-D is added to the model.

**Step 2:** BIM drawing initialization. It belongs to drawing review and upload cycle. BIM-O creates D init and stored in IPFS, and the returned AddrIPFS is obtained. HD is calculated according to D init and then passes HD, AddrIPFS to DAI Cupload. DAI Cupload calculates SigH and combines other relevant information to generate DAI record, then uploads DAI record to BC.

**Step 3:** BIM drawing acquisition and design. It belongs to the drawing design cycle. BIM-D obtains the latest BIM drawing for design. BIM-D first uses DAI Cdownload to acquire DAI record from BC, and then verifies...
whether $H_D$ has been tampered. If not, BIM_D obtains $D_{new}$ from the IPFS according to the $Addr_{IPFS}$, verifies the correctness of $D_{new}$, then designs on $D_{new}$ that has not been tampered.

Before the end of the drawing design cycle, BIM_D uses SDT method to obtain $DDI$ and calculate $HDDI$, and then $HDDI$ is transferred to $DDI_C upload$. $DDI_C upload$ calculates $SigH_{DDI}$, combines other relevant information to generate $DDI$ record and uploads it to BC.

Step 4: BIM drawing design information fusion. It belongs to the drawing design information fusion cycle. BC automatically uses $DDI_C download$ to obtain each $DDI$ record and verifies whether $HDDI$ and $DDI$ have been tampered. If not, SDT method is used to merge all $DDI$ into $DDFI$. $DDI_C download$ calculates $HDFFI$ and combines other relevant information to generate $DDFI$ record. Finally, $DDI_C download$ merges $DDFI$ record to BC.

Step 5: BIM drawing update and upload. It belongs to the drawing review and upload cycle. BIM_O uses $DFDI_C download$ to obtain $DFDI$ record from the BC, and then verifies whether $DFDI$ in it has been tampered. If not, SDT method is used to update local BIM drawing of BIM_O according to $DFDI$, then store $D_{update}$ to IPFS. Finally, generate $DAI$ record and upload it into BC.

**Detailed structure and process design of BIM drawing multi-person collaborative design model**

Corresponding to the model designed in the previous section, this section introduces the detailed structure and related processes of the model.

**Global configuration.** When new BIM_O or BIM_D join the model, CA automatically generates public/private key pair for him/her. As shown in Fig. 6, $RAND_KEY$ needs to re-input when its length is less than 36.
BIM drawing initialization. The multi-person collaborative design process of BIM drawing starts with the drawing review and upload cycle. In the first drawing review and upload cycle, BIM_O creates $D_{init}$ for drawing initialization. In order to explain the operation of BIM_O during this cycle, the complete operation process of BIM_O is first shown in Fig. 7. The initial steps of BIM drawing correspond to serial number ➀, and serial number ➁ corresponds to the steps of BIM drawing updating and uploading, which will be introduced in detail in section “BIM drawing update and upload”.

After BIM_O creates $D_{init}$ and uploads it to IPFS, $DAI_{upload}$ is called to calculate and generate $DAI_{record}$ according to the related information of $D_{init}$. $DAI_{record}$ includes the number of BIM drawing, upload time of BIM drawing, public key of BIM_O, $HD\_D$, $Sig_{H\_D}$ and $Addr_{IPFS}$. $HD\_D$ is calculated by SHA256() hash function, and $Sig_{H\_D}$ is generated by using the private key of BIM_O. $Addr_{IPFS}$ is obtained by hashing $D_{init}$ and Base58 encoding inside IPFS.

BIM drawing acquisition and design. Related operations of BIM drawing acquisition and design are completed by BIM_D within drawing design cycle. The complete process is shown in Fig. 8.

At the beginning of the drawing design cycle, BIM_D obtains $D_{new}$ for design according to the judgment process of number ➀ in Fig. 8 (Assuming BIM_D has learned design requirements of this BIM drawing through other means, $D_{new}$ does not contain any design requirements). Algorithm 1 gives the pseudocode corresponding to the sequence number ➀ processing flow. Firstly, BIM_D obtains $DAI_{record}$ from BC and verifies whether $HD\_D$ has been tampered:

1. BIM_D has BIM drawing locally. If $HD\_D$ has not been tampered, compare $HD\_D$ and $H_{loc}$:
   - If equal. It means BIM_D has latest BIM drawing locally, and then BIM_D designs directly.
   - If not equal. BIM_D obtains $D_{new}$ from IPFS through $Addr_{IPFS}$ and verifies the correctness of $D_{new}$. If verification passed, BIM_D designs on $D_{new}$, and updates $H_{loc}$ to $HD\_D$.

If $HD\_D$ is tampered, BIM_D needs to acquire the latest $HD\_D$ from BC which has not been tampered, and obtains BIM drawing from IPFS through $Addr_{IPFS}$ for the next design.
2. BIM_D has no BIM drawing locally. If \(H_D\) has not been tampered, BIM_D obtains \(D_{new}\) from IPFS and verifies the correctness of \(D_{new}\), design on \(D_{new}\) which has not been tampered, saves \(H_D\) locally as \(H_{loc}\) in order to determine whether \(D_{new}\) is the latest BIM drawing. If \(H_D\) has been tampered, notify BIM_O to regenerate and upload \(D_{new}\).
Figure 8. The operation process of BIM drawing designer.
The above judgment processes involve digital signature verification of HD and Dnew. The verification process is shown in Fig. 9. First, digital signature is decrypted with the public key of corresponding user to obtain encrypted digest. Secondly digest is obtained by re-hashing the original Dnew, and compare whether the two digests are equal. If equal, means Dnew has not been tampered; otherwise, means Dnew has been tampered and requires further processing by BIM_O. Each verification process of digital signature in this paper are the same, just replace the digital signature, Dnew, and public key in Fig. 9 to unverified content, its digital signature, and public key of corresponding user.

For some reasons, BIM_D may not calculate DDI in time at the end of the period of drawing design cycle A, and BIM_D may also not reacquire Dupdate at the beginning of next drawing design cycle B. In this case, at the end of drawing design cycle B, the uploaded DDI by BIM_D is actually from cycle A, not in cycle B. It will lead to an error when update BIM drawing in next drawing review and upload cycle during. Considering above possible problem, before BIM_D uses SDT method to calculate DDI in drawing design cycle, it needs to verify whether BIM_D is designed on Dnew, as shown in Fig. 8 ②.

Figure 9. Digital signature verification process.

Algorithm 1 BIM drawing acquisition

**Input:** local BIM drawing $D_{loc}$ of BIM_D

**Output:** status code (0: existing locally, no need to obtain; 1: obtained successfully), the latest BIM drawing obtained

1: call $DAI_{\text{download}}$ to get $DAI_{\text{record}}$;

2: parse $DAI_{\text{record}}$ to get parameter $H_D$, $Addr_{\text{IPFS}}$;

3: if $D_{loc} \neq \text{NULL} \&\& H_{loc} = H_D$ then

4: output 0, $D_{loc}$;

5: else

6: get $D_{new}$ from IPFS according to $Addr_{\text{IPFS}}$;

7: $H_{loc} = H_D$;

8: output 1, $D_{new}$;

9: end if
After the above relevant verifications are passed, SDT method is used to calculate DDI in drawing design cycle. BIM drawing is exported to IFC or IFCXML files at the beginning and before the end of drawing design cycle (in this paper, BIM drawings uniformly use IFCXML format). Calculating contents of two files to get DDI in drawing design cycle through jsondiff library of Python. DDI only contains the content difference information of BIM drawing before and after this drawing design cycle, which reduces the information redundancy. As shown in Fig. 10, red and green boxes respectively indicate time and wall length at the beginning and end of
drawing design cycle, which show the differences between files before and after the design. The DDI of time and wall length in blue boxes can be calculated through the calculation method of DDI.

Then BIM_D decides whether to upload DDI during this drawing design cycle and whether to continue designing BIM drawing. As shown in number ② and ③ in Fig. 8. If BIM_D needs to upload DDI, BIM_D will use DDI_Cupload to upload DDI_record (includes DDI, start time of drawing design cycle, end time of drawing design cycle, public key of BIM_D, HDDI and SigH_DDI) to BC. BIM drawing design information fusion. There are large numbers of BIM_D in actual scenarios, and there are many DDI uploaded at the end of drawing design cycle. It will be very cumbersome to obtain these DDI separately to update BIM drawing. In order to facilitate BIM_O to update BIM drawing, DDI_Cdownload will be automatically executed by BC to merge all DDI into DFDI and upload it to BC after each BIM_D uploads DDI to BC. Therefore, BIM_O only needs to obtain DFDI once to complete the update of BIM drawing.

In drawing design information fusion cycle, DDI_Cdownload obtains DDI_record and verifies whether DDI in DDI_record has been tampered through digital signature in Fig. 9. If validation passed, DDI is merged into DFDI through SDT method. A specific example is shown in Fig. 11. DDI in BIM_D-1 was calculated through SDT method in Fig. 10, as shown in the green font; DDI in BIM_D-2 mainly includes attribute information of newly added window, as shown in the blue font. The DDI fusion rule use the rule in SDT method, as follows: If there is no conflict in DDI, just merge directly, otherwise delete all conflicting DDI. According to the DDI fusion rule, since DDI in BIM_D-1 and BIM_D-2 both have changes of design date (as shown in red font), delete all the conflicting DDI of date, and then merge the remaining non-conflicting DDI directly to get DFDI.

Finally, DDI_Cdownload combines DFDI, start time and end time of drawing design cycle, HDDI into DFDI_record and uploads it to BC through DFDI_Cupload for BIM_O to update BIM drawing in the next step.

BIM drawing update and upload. When entering the drawing review and upload cycle again, BIM_O will perform operations of BIM drawing update and upload shown in Fig. 7 ②. Except for the new operation of calling DFDI_Cdownload to obtain DFDI and using SDT method to update BIM drawing, the other operations are the same as initialization of BIM drawing, so it is not repeated here. We give the pseudocode of the BIM drawing update operation, as shown in Algorithm 2 (corresponding to the processing flow in the loop body of number ② in Fig. 7).
The SDT method is introduced through a BIM drawing update example. Figure 12 shows an example of BIM drawing update. The DFDI in Fig. 12 obtained from Fig. 11. The green font is the DDI obtained by changing the wall length in BIM_D-1, and the blue font is the DDI obtained by adding a window component to BIM_D-2. DFDI updates BIM drawing method as follows: traverse the hierarchical relationship of component element in DFDI, find the component element attribute of the corresponding hierarchical relationship in BIM drawing before update and make corresponding changes. If the corresponding component element attribute is not found, directly add attributes directly to BIM drawing before the update. Therefore, after updating with DFDI, the length attribute of wall changed from 4000 mm in BIM drawing at the beginning of drawing design cycle to 2000 mm in D update, the relevant attributes of window component is also added in D update.

Consensus algorithm used in the model. Raft is used as the consensus mechanism of BC in this paper. It is a distributed consensus mechanism, which is widely used in consortium blockchains. Raft is mainly used to manage the consistency of log replication which can solve the problem of information synchronization in the multi-person collaborative design of BIM drawing. Meanwhile, Raft can tolerate 50% non-Byzantine nodes, and using this mechanism can improve the stability of the multi-person collaborative design model of BIM drawing.
There are 3 roles in the nodes of Raft: the follower, the candidate, and the leader. The consensus process includes leader election and log replication. In this paper, the consensus process is described as follows:

1. Leader election: This election is random. BIM_O or BIM_D nodes can be elected as leader. Only leader can process requests initiated by BIM_O or BIM_D. Followers will forward the requests to leader for processing after receiving requests, while candidates will directly reject.
2. **Log replication:**

   ➀ BIM_O or BIM_D sends a request for obtaining or uploading BIM drawing data to the leader, and the leader processes request and sends to other BIM_O and BIM_D nodes, waiting to receive responses from BIM_O and BIM_D nodes; ➁ consensus is reached when leader received the confirmation responses from most nodes, leader first executes the request on the local ledger, and then informs other nodes that the consensus has reached; ➂ after receiving the notification of "consensus reached" from leader, other nodes also execute the request in the local ledger, and finally achieve the consistency of the request, that means reach the consensus.

**Experimental verification and evaluation analysis**

Firstly, this section compares and analyzes the proposed scheme with existing blockchain-based scheme of BIM collaborative design. Subsequently, the performance and consistency of BIM drawing in the model are tested and evaluated through multi-machine experimental environment. The safety and reliability of data in the model is guaranteed by the characteristics of blockchain itself. The problem of redundancy of BIM drawing design information has been tested and analyzed in literature and will not be repeated here. At the end of this section, the security and reliability of proposed model are evaluated, and an actual scenario is used as an example to verify the effectiveness of the multi-person collaborative design model proposed in this paper.

---

**Figure 13.** System experiment environment deployment.
Scheme comparison. The comparison between proposed scheme and other existing schemes is shown in Table 1.

Tao et al.²² adopted the storage method combining on-chain and off-chain to reduce the storage pressure of blockchain. With only storing the summary of BIM design operation information in blockchain, accurate design content cannot be provided, and thus it cannot be used as an effective copyright proof. Therefore, proposed scheme and literatures²⁴,²⁵ stored the BIM design content in blockchain to protect designer’s copyright interests. However, literatures²⁴,²⁵ have not yet effectively integrated blockchain and BIM during the process of BIM collaborative design, and have not yet addressed issues such as the consistency of BIM drawing versions and the management of safety and reliability.

Although Shen et al.²³ solved the problem of BIM version conflict, their solution is inefficient. Besides, their centralized off-chain storage method has security risks such as single-point failure and data tampering. The storage of large amount of useless design data also leads to information redundancy in blockchain. In response to the above problems in literature²³, this paper uses blockchain and IPFS to realize the collaborative storage of data, so as to ensure the safety and reliability of data (see section Security and reliability analysis). In addition, SDT method and cycle division mechanism are used to realize the incremental update of BIM drawing and reduce information redundancy, which ensure the consistency of BIM drawing and improve the collaborative design efficiency.

Multi-machine experimental environment configuration of the system. The prototype system is built by using the Hyperledger Fabric 1.4 framework.

The experimental equipment is a laptop and two Raspberry Pi 4B. The laptop has 16 GB of memory, an 8-Core Intel Core i7 processor, and three virtual machines with 2 Cores and 2 GB of memory. The virtual machines are all equipped with the Ubuntu 18.04 system. The two Raspberry Pi 4B both have 2 GB of memory, a 4-core Broadcom processor, and are equipped with an Ubuntu 18.04 arm version system. The Raft experimental environment has 5 Orderer Services, 5 organizations, and 5 Peer nodes. Each organization has a Certification Authority (CA) Service and a Peer node. Each node corresponds to a CouchDB. The endorsement policy is set to at least one endorsing node in each organization to participate in the endorsement.

System experiment environment deployment. The deployment of the system experiment environment is shown in Fig. 13. Use the virtual machine client in a laptop or Raspberry Pi to simulate a total of five users of BIM_O and BIM_D. Blockchain nodes are deployed in virtual machines, and all blockchain nodes are connected to each other to form a Hyperledger Fabric blockchain network. There is a total of one application channel and five organizations in the network, and each organization has one user. BIM_O and BIM_D

| Table 4. Time-consuming comparisons of drawing storage, acquisition and contract execution. |
|-------------------------------------------------|-----------------|-----------------|
| Drawing review and upload cycle | Storage of drawing (off-chain) | 27,847 ms | 26,703 ms |
|                                  | Uploading drawing summary information to blockchain (contract) | 710 ms | 747 ms |
| Drawing design cycle | Acquisition of drawing (off-chain) | 1906 ms | 26,159 ms |
|                                  | Uploading drawing update information to blockchain (contract) | 896 ms | 728 ms |
| Drawing design information fusion cycle | Fusing drawing design information (contract) | 7786 ms |
| Total time (single-round design) | | 39,145 ms | 54,337 ms |

Figure 14. Comparison of system transaction throughput.
exchange BIM drawing data with the Hyperledger Fabric blockchain network through the blockchain node in
the corresponding virtual machine. At the same time, BIM_O and BIM_D are also building IPFS nodes locally
and building an IPFS private network to upload and download BIM drawing.

**System performance evaluation.** The BIM drawing used for performance test is a health care center in
Jiangxi Province, China. This center covers an area of about 50,000 square meters, with 5 floors, and the size of
the drawing is 56 MB. According to literature, the test focuses on design time-consuming and throughput. Test
results of proposed scheme are compared with Shen et al. Among them, design time-consuming includes stor-
age/acquisition time of BIM drawing, execution time of contract. They are used to evaluate the design efficiency
of proposed scheme. Throughput is used to evaluate the concurrent efficiency of proposed scheme.

**Design time-consuming assessment.** In the built multi-machine experimental environment, automated script
is written to test storage/acquisition time of BIM drawing and execution time of contract in each cycle of pro-
posed scheme (designing, updating the drawing or other related operations via local software are not influ-
enced by proposed scheme itself, so the related operations will not be discussed here). Test results are compared
with literature, as shown in Table 4. Among them: (1) the operation of drawing storage and acquisition are
implemented based on IPFS in proposed scheme, while it is implemented based on centralized cloud server;
(2) drawing update information in proposed scheme represents the DDI calculated by BIM_D through SDT
method, while it represents the complete information summary of BIM drawing after design.

It can be seen from Table 4 that the acquisition efficiency of drawing is better than that of literature, while
the drawing storage efficiency is slightly lower. BIM_O in proposed scheme needs to synchronize BIM drawing
to other BIM_D through IPFS network when storing the drawing, so it takes longer than only storing the draw-
ing to cloud. When acquiring the drawing, BIM_D in proposed scheme can directly obtain the corresponding
drawing in local IPFS repository according to the storage address, therefore, the acquisition efficiency is high.

However, in literature, remote request needs to be sent to cloud server for acquiring drawing, which takes a
long time in data transmission.

In terms of contract execution, since proposed scheme needs to upload DDI to blockchain, execution time of
storing drawing update information is higher than that in literature (only stores summary or other modification
logs). In addition, proposed scheme designs an additional contract to fuse multiple DDI, and the fusion
result is available for BIM_O to update BIM drawing locally. Based on the above operation, proposed scheme
can realize the incremental update of BIM drawing, reduce information redundancy and reduce the number of
times that BIM_O updates drawing locally, thereby improving the efficiency of collaborative design.

The test results show that time-consuming of single-round collaborative design in proposed scheme is better
than that in literature, which proves that proposed scheme can effectively reduce the design time-consuming of
BIM drawing. Besides, based on the characteristics of IPFS, proposed scheme also ensures the reliability of BIM
drawing and low redundancy (section "Security and reliability analysis" analyzes the reliability of BIM drawing).

**Throughput assessment.** Considering the scenario that multiple BIM_D initiate a large number of design trans-
actions within a period of time, transaction throughput of prototype system is tested based on Hyperledger
Caliper (performance test framework for Hyperledger Fabric). Maximum transaction throughput of blockchain
system is tested when processing a large number of design transactions sent by multiple BIM_D per unit time.
The test environment is set as follows: 4 BIM_D nodes concurrently initiate a total of 400, 600, 800, 1000, 1200,
1400, 1600, and 1800 DDI uploading transactions per unit time. The maximum transaction throughput of block-
chain system is tested, and the results are compared with literature.

The results are shown in Fig. 14. Due to the same experimental environment and no changes of Fabric
architecture, the maximum throughput of proposed scheme and literature are 1112 transactions per second and
1193 transactions per second respectively. The performance difference of throughput can be approximately
ignored. In addition, requirements of performance in actual multi-person collaborative design are far less than

---

**Figure 15.** BIM drawing consistency.
test results. Therefore, performance of proposed scheme can meet the daily requirements of BIM_D and system, which can ensure the availability and effectiveness of proposed scheme.

**Performance analysis of BIM drawing update operation.** In view of the scenario where BIM_O updates multiple BIM drawing during the drawing review upload cycle, the performance of the BIM drawing update operation is analyzed. The performance is related to the time complexity of the BIM drawing update algorithm. The following focuses on the analysis of the time complexity of the BIM drawing update algorithm.

The BIM drawing update algorithm completes the update through two traversals. First, it traverses $DFDI$ to obtain the hierarchical relationship of the element attributes of the BIM drawing component to be updated, and then traverses the content of the BIM drawing before the update to find and update the attribute of the BIM drawing component corresponding to the hierarchical relationship. Among them, the update operation includes modification, addition, or deletion, and is executed only once, and the time complexity is $O(1)$. Therefore, the time complexity of the BIM drawing update algorithm mainly depends on the time complexity of the traversal operation.

Recursively traverse $DFDI$ and BIM drawing content before updating. Set the BIM drawing component element attribute levels of the $DFDI$ and the BIM drawing content before the update to $m$ and $n$ and $m > n$, then the time complexity of the two traversals are $O(m)$ and $O(n)$ respectively. The time complexity of the BIM drawing update algorithm depends on the larger one of $m$ and $n$, and the time complexity is linear time complexity $O(m)$. In summary, the BIM drawing update operation performance is better, and it does not affect the overall operating efficiency of the system.

**Test of BIM drawing consistency.** The model proposed in this paper ensures that BIM drawing obtained by BIM_D from IPFS can remain consistent after multiple rounds of design, that is, obtained BIM drawing have the same content. A round of design refers to starting from the drawing review upload cycle, after the drawing design cycle and the drawing design information integration cycle, and then returning to the drawing review upload cycle. The test is achieved by writing test scripts. The test environment is set as follows: 4 BIM_D perform 1,000 rounds of design on the initial blank BIM drawing. Each round must ensure that at least one BIM_D
Figure 17. BIM drawing summary information in blockchain ledger.

2.2a Download DRev

2.2b Download DRev

2.3b Design and calculate DDI

2.3g Design and calculate DDI

2.4a Store DDI\textsubscript{record}

2.4b Store DDI\textsubscript{record}

2.1a Get DAI\textsubscript{record} from BC

2.1b Get DAI\textsubscript{record} from BC

Transaction data (BIM\textsubscript{D-1})

Transaction data (BIM\textsubscript{D-2})

Figure 18. Example: BIM\textsubscript{D} design BIM drawing.
designs the drawing. The design content is not limited but must be quite different from the pre-design drawing. The purpose of test is to verify whether the contents of BIM drawing obtained by different BIM_D from IPFS are consistent.

The test results are shown in Fig. 15. During rounds 352 to 406 and 641 to 677, the number of consistent BIM drawing decreases to 3. The inconsistency of drawing is caused by faults such as disconnection and downtime of individual nodes. After the node recovers from fault, the number of consistent BIM drawing becomes 4 again. The experimental results show that proposed model has good robustness. In addition, proposed model can ensure that all BIM_D design on the same BIM drawing when no faulty node exists, thereby meeting the design requirements for ensuring the consistency of BIM drawings during the process of multi-person collaborative design.

Security and reliability analysis. This section analyzes the multi-person collaborative design model proposed in this paper from the perspective of security and reliability. The analysis contents include:

1. User permission problem. BIM_O can set the modification right of the BIM drawing when initializing the BIM drawing, and specify which user (BIM_O) has the right to participate in the design of the BIM drawing (edit/modify/delete related data components in the drawing). In addition, BIM_O can dynamically update the modification right list in the subsequent creation process to avoid malicious tampering of the BIM drawing content by illegal users, thereby ensuring the normal operation of the multi-person collaborative design process.

2. The problem of key loss. In the process of multi-person collaborative design of BIM drawing, the problem of key loss may occur: ➀ If BIM_D loses the private key, BIM_D can re-apply for the public and private key from the CA. After proving BIM_D's identity offline, BIM_O updates the list of modification rights, adds
the new public key of BIM_D to it, and removes the original public key; ➁ If BIM_O loses the private key, after reapplying for the public and private keys, BIM_O needs to negotiate with all BIM_D offline to prove identity, and distribute the new public key to each BIM_D. In the subsequent collaborative design process, BIM_D uses the new public key to verify the signature and identity of BIM_O.

3. The reliability of BIM drawing. In this model, the reliability of BIM drawing stored in IPFS and drawing design information stored in BC is guaranteed by the cryptographic algorithm and distributed storage features within IPFS and BC. BIM_D or BIM_O firstly judges the validity and authenticity of BIM drawing and related information by verifying signatures before designing and updating drawing. Then operate on the basis of valid BIM drawing or related information that have passed the verification, so as to ensure the reliability of BIM drawing in the entire collaborative design process.

Illustration example. In order to further illustrate the effectiveness of the model proposed in this paper, this section takes the modification of the wall in the BIM drawing of the health care center as an example to introduce the multi-person collaborative design process of BIM_O and BIM_D in the constructed prototype system.

Step1: BIM_O creates initial BIM drawing. As shown in Fig. 16, in the drawing review and upload cycle, BIM_O first creates $D_{init}$, then uploads it to the IPFS network, and then obtains the returned $\text{AddrIPFS}$ (e.g., “QmfY qMFX…iRG5Uzbv” in Fig. 16). After that, construct $\text{DAI record}$ and store it into BC. Figure 17 shows the specific transaction information of $\text{DAI record}$ in the BC ledger (CouchDB), where “DRAW001” represents the ID number of the drawing.

Step2: BIM_D design BIM drawing. BIM_D-1 intends to modify the width of the wall in the BIM drawing, and BIM_D-2 intends to add a window on the wall. The design flow is shown in Fig. 18. At different time points in the same drawing design cycle (the design time of each round is fixed at 2 h, the start time of this round is 2021–03-03 13:00:00, and the end time is 2021–03-03 15:00:00), they get the summary information of the drawing numbered “DRAW001” from BC, and download the latest BIM drawing from IPFS according to $\text{AddrIPFS}$. Subsequently, they each carry out the drawing design locally, and calculate the corresponding $\text{DDI}$ based on the SDT method after the design was completed. Finally, BIM_D-1 and BIM_D-2 call the smart contract to construct $\text{DDI record}$ at different time points and store it in the BC ledger (as shown in Fig. 19).

Step3: BIM_O update BIM drawing. Figure 20 shows the process of BIM_O updating BIM drawing. After the drawing design cycle ends, it will enter the drawing design information fusion cycle. In the drawing design information fusion cycle, BC will automatically execute $\text{DDI_Cdownload}$ to fuse all $\text{DDI}$ to generate $\text{DFDI}$. BIM_O
calls the smart contract to obtain \( D_{DFDI} \) from BC, and then uses \( D_{DFDI} \) to update the local drawing content to get \( D_{update} \). Finally, BIM\(_O\) uploads \( D_{update} \) to the IPFS network, then creates \( DA_{record} \) and stores it in BC.

At this point, the multi-person collaborative design process of BIM drawing is over. If BIM\(_D\) or BIM\(_O\) still has other design requirements, BIM\(_D\) and BIM\(_O\) will repeat the steps in sections “Step2: BIM\(_D\) design BIM drawing” and “Step3: BIM\(_O\) update BIM drawing” until BIM\(_O\) terminates the design of BIM drawing.

**Conclusion**

In large-scale construction projects, multi-person collaborative design of BIM drawing is very important, which can greatly improve the efficiency of BIM drawing design, accelerate the construction of construction projects, and promote the continuous development of construction field. In order to solve the problems of poor data security and reliability, inconsistent BIM drawing information, information redundancy, and inaccurate protection of copyright interests in the existing multi-person collaborative design methods of BIM drawing, this paper proposes a multi-person collaborative design model for BIM drawing based on the collaborative storage of blockchain (on-chain) and IPFS (off-chain). This model stores the encrypted drawing data through a collaborative method, which not only ensures the security, reliability and integrity of data, but also improves the scalability of blockchain. Besides, this model uses a period division mechanism to avoid the problem of information synchronization during the process of BIM drawing design. It uses the SDT method to achieve incremental updates of BIM drawing, reduce information redundancy, and uses blockchain to record the designer’s incremental design information to provide designers with the accurate copyright basis. Finally, the experiment is designed to test the performance and security of proposed scheme, and the example is used to demonstrate the usability of proposed scheme.

Although this paper has built an efficient and usable multi-person collaborative design model of BIM drawing based on blockchain, it also has some shortcomings. The step of BIM drawing design information fusion in the model takes extra time to complete, which will have a certain impact on the model efficiency. Therefore, in future research work, we consider combining the fusion process of BIM drawing design information with the consensus process of blockchain to complete the information fusion in consensus process and avoid additional time overhead. In addition, the performance of SDT method needs to be advanced to further improve the efficiency of handling large-scale BIM drawing information.

**Data availability**

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Received: 14 October 2021; Accepted: 9 September 2022

Published online: 29 September 2022

**References**

1. Succar, B. Building information modelling framework: A research and delivery foundation for industry stakeholders. Autom. Constr. 18, 357–375 (2009).
2. Succar, B. & Kassem, M. Macro-BIM adoption: Conceptual structures. Autom. Constr. 57, 64–79 (2015).
3. Gao, X. & Pishdad-Bozorgi, P. BIM-enabled facilities operation and maintenance: A review. Adv. Eng. Inform. 39, 227–247 (2019).
4. Tang, S., Shelden, D. R., Eastman, C. M., Pishdad-Bozorgi, P. & Gao, X. A review of building information modeling (BIM) and the internet of things (IoT) devices integration: Present status and future trends. Autom. Constr. 101, 127–139 (2019).
5. Stm, A., Da, A., Ab, A., Mg, A. & Rm, B. Building information modeling for facilities management: A literature review and future research directions. J. Build. Eng. 24, 100735 (2019).
6. Logothetis, S., Karachaliou, E., Valari, E. & Stylianidis, E. Open source cloud-based technologies for BIM. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. 42, 607–614 (2018).
7. Zheng, J. Analysis of collaborative design and construction collaborative mechanism of cloud BIM platform construction project based on green computing technology. J. Intell. Fuzzy Syst. 34, 819–829 (2018).
8. Di Mascio, D., & Wang, X. Building Information Modelling (BIM)-supported cooperative design in sustainable renovation projects. Int. Journal on Cooperative Design, Visualization and Engineering. 205–212 (Springer, 2013).
9. Studnia, L., Alata, E., Deswarte, Y., Kaâniche, M., & Nicomette, V. Survey of security problems in cloud computing virtual machines. In Computer and Electronics Security Applications Rendez-vous (C&ESAR 2012), 61–74 (CCSD, 2012).
10. Afedzi, N., Alabdulatif, A., Iwendi, C. & Lian, Z. SVBE: Searchable and verifiable blockchain-based electronic medical records system. Sci. Rep. 12, 1–11 (2022).
11. Yuan, Y. & Wang, F. Y. Blockchain: The state of the art and future trends. Acta Autom. Sin. 42, 481–494 (2016).
12. Qiao, R., Liu, A. D., Chen, D. & Wang, Q. X. Communication mechanism of IoT consortium chain in complex scenarios. Acta Autom. Sin. https://doi.org/10.16383/j.aaas.c200106 (2020).
13. Lin, C., He, D., Huang, X., Choo, K. K. R. & Vasilakos, A. V. BSeN: A blockchain-based secure mutual authentication with fine-grained access control system for industry 4.0. J. Netw. Comput. Appl. 116, 42–52 (2018).
14. Zhang, L., Zheng, Z. Y. & Yuan, Y. A controllable sharing model for electronic health records. Acta Autom. Sin. https://doi.org/10.16383/j.aas.c2000359 (2021).
15. Turk, Ž & Klinček, R. Potential of blockchain technology for construction management. Procedia Eng. 196, 638–645 (2017).
16. Liu, Z., Jiang, L., Osmani, M. & Demian, P. Building information management (BIM) and blockchain (BC) for sustainable building design information management framework. Electronics 8, 724 (2019).
17. Yang, R. et al. Public and private blockchain in construction business process and information integration. Autom. Constr. 118, 103276 (2020).
18. Zheng, R. et al. bcBIM: A blockchain-based big data model for BIM modification audit and provenance in mobile cloud. Math. Probl. Eng. 2019, 1–13 (2019).
19. Ni, Y., Sun, B. & Wang, Y. Blockchain-based BIM digital project management mechanism research. IEEE Access 9, 161342–161350 (2021).
20. Kasten, J. E. Engineering and manufacturing on the blockchain: A systematic review. IEEE Eng. Manage. Rev. 48, 31–47 (2020).
21. Duan, X. B. & Wang, B. F. Blockchain-based BIM model security management method for rail transit. Railway Stand. Design 64, 136–140 (2020).
22. Tao, X., Das, M., Liu, Y. & Cheng, J. C. Distributed common data environment using blockchain and Interplanetary File System for secure BIM-based collaborative design. Autom. Constr. 130, 103851 (2021).
23. Shen, Y. M., Wang, J. L., Hu, D. K. & Liu, X. Y. Multi-person collaborative creation system of building information modeling drawings based on blockchain. J. Comput. Appl. 41, 2338–2345 (2021).
24. Das, M., Tao, X. & Cheng, J. C. BIM security: A critical review and recommendations using encryption strategy and blockchain. Autom. Constr. 126, 103682 (2021).
25. Xue, F. & Lu, W. A semantic differential transaction approach to minimizing information redundancy for BIM and blockchain integration. Autom. Constr. 118, 103270 (2020).
26. Shafig, M. T., Matthews, J. & Stephen, R. A study of BIM collaboration requirements and available features in existing model collaboration systems. J. Inform. Technol. Constr. (Ticon) 18, 148–161 (2013).
27. van Berlo, L. & Krijnen, T. Using the BIM collaboration format in a server based workflow. Procedia Environ. Sci. 22, 325–332 (2014).
28. Zada, A. J., Tizani, W. & Oti, A. H. Building information modelling (BIM)—Versioning for collaborative design. In Computing in Civil and Building Engineering, 512–519 (ASCE, 2014).
29. Moayeri, V., Moselhi, O. & Zhu, Z. Design change management using BIM-based visualization model. Int. J. Archit. Eng. Constr. 6, 1–11 (2017).
30. El Diraby, T., Krijnen, T. & Papagalos, M. BIM-based collaborative design and socio-technical analytics of green buildings. Autom. Constr. 82, 59–74 (2017).
31. Poerschke, U., Holland, R. J., Messner, J. I., & Pihlak, M. BIM collaboration across six disciplines. In Proceedings of the International Conference on Computing in Civil and Building Engineering, 575–671 (2010).
32. Singh, V., Gu, N. & Wang, X. A theoretical framework of a BIM-based multi-disciplinary collaboration platform. Autom. Constr. 20, 134–144 (2011).
33. Liu, F., Jallow, A. K., Anumba, C. J. & Wu, D. A framework for integrating change management with building information modeling. Comput. Civ. Build. Eng. 5, 439–446 (2014).
34. Logothetis, S., Karachalios, E., Vlahi, E. & Stylianidis, E. Open source cloud-based technologies for BIM. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci 42, 607–614 (2018).
35. Wang, J., Wu, P., Wang, X. & Shou, W. The outlook of blockchain technology for construction engineering management. Front. Eng. Manage. 4, 67–75 (2017).
36. Risiu, M. & Spohrer, K. A blockchain research framework. Bus. Inf. Syst. Eng. 59, 385–409 (2017).
37. Nawari, N. O. & Ravindrana, S. Blockchain and building information modeling (BIM): Review and applications in post-disaster recovery. Buildings 9, 149 (2019).
38. Winfield, M. The winfield rock report: Overcoming the legal and contractual barriers of BIM. In Proc. Winfield Rock Report Overcoming the Legal and Contractual Barriers BIM 1–60 (2018).
39. Dakhli, Z., Lafhaj, Z. & Mossman, A. The potential of blockchain in building construction. Buildings 9, 77 (2019).
40. Elghaish, F., Abrishami, S. & Hosseini, M. R. Integrated project delivery with blockchain: An automated financial system. Autom. Constr. 114, 103182 (2020).
41. Wen, S., Xiong, W., Tan, J., Chen, S. & Li, Q. Blockchain enhanced price incentive demand response for building user energy network in sustainable society. Sustain. Cities Soc. 68, 102748 (2021).
42. Van Cutsem, O., Das, D. H., Boudou, P. & Kayal, M. Cooperative energy management of a community of smart-buildings: A blockchain approach. Int. J. Electr. Power Energy Syst. 117, 105643 (2020).
43. Das, M., Tao, X., & Cheng, J. C. A secure and distributed construction document management system using blockchain. In International Conference on Computing in Civil and Building Engineering 850–862 (Springer Cham, 2020).
44. Wang, Z. et al. Blockchain-based framework for improving supply chain traceability and information sharing in precast construction. Autom. Constr. 111, 103063 (2020).
45. Lee, D., Lee, S. H., Masoud, N., Krishnan, M. S. & Li, V. C. Integrated digital twin and blockchain framework to support accountable information sharing in construction projects. Autom. Constr. 127, 103688 (2021).
46. Das, M., Luo, H. & Cheng, J. C. Securing interim payments in construction projects through a blockchain-based framework. Autom. Constr. 118, 103284 (2020).
47. Li, C. Z. et al. A blockchain-and IoT-based smart product-service system for the sustainability of prefabricated housing construction. J. Clean. Prod. 286, 125391 (2021).
48. Sheng, D. et al. Construction quality information management with blockchains. Autom. Constr. 120, 103373 (2020).
49. Lokshina, I. V., Gregori, M. & Thomas, W. L. Application of integrated building information modeling, IoT and blockchain technologies in system design of a smart building. Procedia Comput. Sci. 160, 67–70 (2020).
50. Nawari, N. O. & Ravindra, S. Blockchain and the built environment: Potentials and limitations. J. Build. Eng. 25, 100832 (2019).
51. Li, J., Greenland, D. & Kassem, M. Blockchain in the built environment and construction industry: A systematic review, conceptual models and practical use cases. Autom. Constr. 102, 288–307 (2019).
52. Deng, Y., Gan, V. J., Das, M., Cheng, J. C. & Anumba, C. Integrating 4D BIM and GIS for construction supply chain management. J. Constr. Eng. Manag. 145, 04019016 (2019).
53. Nawari, N. O. & Ravindra, S. Blockchain technology and BIM process: Review and potential applications. J. Inf. Technol. Constr. 24, 209–238 (2019).
54. Li, J., Kassem, M., Ciribini, A. L. C., & Bolpagni, M. A proposed approach integrating DLT, BIM, IoT and smart contracts: Demonstration using a simulated installation task. In International Conference on Smart Infrastructure and Construction 2019 (ICSCIC) Driving data-informed decision-making 275–282 (2019).
55. Dounas, T., Lombardi, D., & Jabi, W. Towards blockchains for architectural design consensus mechanisms for collaboration in BIM. In Proceedings of 37 eCAADe and XXIII SIGed Joint Conference 267–274 (2019).
56. Liu, M. D., Chen, Z. N., Shi, Y. J., Tang, L. T. & Cao, D. Research progress of blockchain in data security. Chin. J. Comput. 44, 1–27 (2021).
57. Steichen, M., Fiz, B., Norvill, R., Shbait, W., & State, R. Blockchain-based, decentralized access control for IPFS. In 2018 IEEE International Conference on Internet of Things (iThings) and IEEE Green Computing and Communications (GreenCom) and IEEE Physical, Social and Cultural Computing (CPSCom) and IEEE Smart Data (SmartData) 1499–1506 (IEEE, 2018).
58. Nyaloteley, E., Parizi, R. M., Zhang, Q., & Choo, K. K. R. BlockIPFS-blockchain-enabled interplanetary file system for forensic and trusted data traceability. In 2019 IEEE International Conference on Blockchain (Blockchain) 18–25 (IEEE, 2019).
59. Ongaro, D. & Ousterhout, J. In search of an understandable consensus algorithm. In 2014 USENIX Annual Technical Conference (Usenix ATC 14), 305–319 (2014).

Author contributions
Y.S. and X.W. conducted the research, Y.S. wrote the main manuscript text. J.W. and X.X. supervised the project and revised the manuscript with X.F. and J. W. All authors analyzed the data, reviewed the manuscript.
Funding
This is a part research accomplishment of the project “National Natural Science Foundation of China (No. 61502262)”, which is supported by National Natural Science Foundation of China. And this is a part research accomplishment of the project "the Key Research and Development Foundation of Shandong Province of China (No. 2019GGX101017)”, which is supported by Department of Science & Technology of Shandong province.

Competing interests
The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to J.W.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

© The Author(s) 2022