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Developing a Blockchain-Based Framework for Digital Archiving of BIM Using Axiomatic Design

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Abstract: Building information modeling (BIM) has been attracting increasing attention in the architecture, engineering, and construction (AEC) industry in recent years. The wide spread of BIM marks the transition from 2D and paper-based archiving to 3D and digital archiving of project information. However, the commonly used centralized managing approaches for BIM data have high risks of data loss and data tampering. With cryptographic algorithms and distributed databases, blockchain has the potential to address the limitations of data loss and trust in conventional BIM management methods. Therefore, this paper proposes a blockchain-based framework for digital archiving of BIM data. In this paper, the axiomatic design approach is utilized to design the archiving framework in order to systematically map the design parameters with the functional requirements and minimize the information contents. The proposed framework contains five modules, including the BIM module, building plan approval (BPA) module, building data simplification (BDS) module, distributed data storage (DDS) module, and digital document verification (DDV) module. Hyperledger Fabric is utilized to develop the blockchain system based on the proposed framework. In the end, a simple BIM model with 240 components and around 11,000 lines of content in the Industry Foundation Classes (IFC) file is taken as an illustrative example to validate the proposed blockchain approach. By storing the BIM model on to the developed blockchain, it is found that each transaction of a blockchain can store over 5000 lines of IFC contents with 0.09 s of uploading latency. The results show that the proposed blockchain-based approach can effectively and securely archive BIM data.

Keywords: axiomatic design; building information modelling (BIM); digital archiving; blockchain

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1. Introduction

The architecture, engineering, and construction (AEC) industry has long been regarded as a highly resource-consuming industry, with tremendous consumption of raw materials and energy [1]. During the various production activities of the AEC industry, huge amounts of documents are accumulated, including construction drawings, bills of materials, business contracts, and construction plans and specifications. Management of such documents among different parties in a project is challenging because the activities in the AEC industry are deeply fragmented, distributed, and specialized [2]. The inefficient management of data caused by the lack of interoperability can lead to serious economic loss [3]. More efficient solutions are required to improve the management, integration, and sharing of information from different data sources.

In recent years, more and more researchers from the AEC industry have started to explore the implementation of building information modeling (BIM), which can facilitate the exchange and interoperability of data in digital format [4]. The rich information in BIM, including both geometric information and semantic (non-geometric) information, can be used to replace the conventional computer-aided design (CAD) drawings and various documents of a project. The wide spread of BIM marks the transition from 2D and paper-based archiving to 3D and digital archiving of project information. In the early years of BIM implementation or some small BIM projects, BIM data are mainly stored on people's individual computers independently, which limits the collaboration among different teams of a project. Nowadays, centralized management of BIM data using web services, central servers, and data centers has been widely applied [5,6], which greatly promotes collaborative management of BIM. However, there are two major limitations when BIM data are stored separately by numerous parties or stored centrally in a single data center. Firstly, if any points in the centralized data structure or an individual computer fails, serious loss of data occurs. The data loss is irrecoverable if there is no efficient backup. Secondly, there is a risk of tampering with these two conventional BIM archiving approaches. Any party involved in the project has the opportunity to tamper with the BIM data, which greatly reduces the authenticity of the BIM data. In the AEC industry, trust issues always exist among different teams when data are provided by others [7].

Since the emergence of bitcoin in 2009, people have gradually realized the value of the blockchain in data management [8]. A blockchain is a growing list of records (blocks) that are linked using cryptography [8]. Blockchain utilizes cryptographic algorithms and distributed databases to achieve a transparent and secure archiving of digital data. Each block in a blockchain contains a set of transaction records with a unique hash value [9]. The identity of every block is defined by its own hash value and that of the previous blocks in the chain, making it practically impossible for any thirty party to tamper with the data [10]. Due to its decentralized nature, the blockchain has the potential to address the limitations of data loss and trust in conventional BIM-archiving approaches. The public ledger of blockchain has been hailed as an excellent example of transactional transparency, while its features of decentralization can be an excellent fit for the fragmented nature of the AEC industry [11].

Some studies have been conducted to evaluate the integration of BIM with a blockchain. Li et al. [12] discussed the potential of applying a blockchain to BIM management in a review paper about a blockchain in a built environment. Chong and Diamantopoulos [13] proposed a BIM and blockchain-based framework to address security of payment (SOP) issues. The existing studies in this field mainly focus on a theoretical discussion or focus on finance and contracts only [13,14]. Some researchers have developed blockchain prototypes for BIM data storage and implemented them in real projects [15–17]. However, in order to practically utilize blockchain technology for archiving BIM data, the developed blockchain can be further improved by maintaining the independence of functional requirements and minimizing the information contents. Therefore, in order to fill this research gap, this paper utilizes axiomatic design to develop a blockchain-based framework for BIM data archiving. Compared with previous studies about blockchain-BIM integration, this paper utilizes the axiomatic design approach to fully analyze the inner relationships among functional requirements and system contents. The developed framework can minimize the blockchain system complexity while fully meeting all functional requirements.

In this paper, an axiomatic design approach [18] is applied to develop the archiving framework, which can systematically map the design parameters with functional requirements. Integrated Computer-Aided Manufacturing Definition (IDEF) [19] diagram language is adopted to conduct the axiomatic design. The developed framework includes five modules, namely, the BIM module, the building plan approval (BPA) module, the building data simplification (BDS) module, the distributed data storage (DDS) module, and the digital document verification (DDV) module. After the development of the framework, Hyperledger Fabric was utilized to develop the blockchain system. In the end, this study takes a simple BIM model as an illustrative example to validate the proposed blockchain approach, which has proved to be feasible and efficient according to the validation results.

This paper proposes a blockchain-based framework for digital archiving of BIM models. The framework is designed and verified using the axiomatic design approach. Section 2 conducts a literature review on existing archiving approaches for BIM data and blockchain applications in the AEC industry. Section 3 briefly introduces the methodology of this paper. The details of the framework development are described in Section 4, and the framework verification is provided in Section 5. Section 6 discusses the results of the experimental validation. The conclusions summarize the contribution and limitations of this research.

2. Literature Review

2.1. Storage and Archiving of BIM Data

With the rapid development of computer science, 3D modeling is attracting increasing attention in the AEC industry. BIM, which contains both geometric information and semantic information, can be used to track, update, and maintain information on building facilities throughout a building's whole lifecycle [20]. BIM has the potential to improve the interoperability and exchange of data in digital format to achieve better decision making in design, construction, and operations [21]. The rich information contained in BIM plays an important role in design evaluation, construction cost estimation, construction management, facility operations, and maintenance [22]. As a result, BIM has been more and more widely used in the AEC industry in recent years, as illustrated in some review papers [23,24].

Traditionally, building information is stored in 2D paper drawings and paper documents. With the emergence of BIM technology, the archiving of building information gradually transits from paper-based archiving to digital archiving [25]. Serving as a single source of truth, BIM can greatly improve the efficiency of data storage and retrieval, thus improving the efficiency of various management activities in a building's whole life cycle [26]. According to the BIM maturity levels stated in the Government Construction Strategy by the United Kingdom (UK) government, the BIM levels include (1) BIM level 0, which refers to 2D CAD drawings; (2) BIM level 1, which refers to 2D drawings and 3D digital models; (3) BIM level 2, which refers to standardized BIM formats enabling information sharing among different parties; and (4) BIM level 3, which refers to standardized management of BIM data throughout the whole life cycle of projects [27]. The storage of BIM data also varies at different BIM levels. For example, it is required in BIM level 3 that the project models be managed on BIM collaboration servers so that participants can review and modify the BIM data through the cloud simultaneously. It can be seen that with the improvement in BIM maturity, the storage of BIM data is also changing.

In early BIM applications, BIM data are normally stored on each individual's computer. With the promotion and spread of BIM collaboration, centralized management of BIM data based on web services, central servers, and data centers is more and more widely applied. For example, Jiao et al. [5] proposed a cloud-based centralized data structure to store BIM information for collaboration among multiple enterprises. Chen and Hou [6] developed an asynchronous network system that could enable multiple design teams to work simultaneously on a single BIM project. Ma et al. [28] developed a dedicated collaboration system for integrated project delivery (IPD) based on an open-source collaboration platform and BIM server. Even for some recent research in 2020 [29,30], people are still focusing on this centralized archiving of BIM data. It can be illustrated that the centralized storage of BIM data is the most popular method for BIM archiving nowadays.

However, any critical failure at single points in the above-mentioned BIM archiving infrastructure, which can be a personal computer of an individual or a central server, can lead to serious loss of data. Without efficient backup, the data loss is irrecoverable and can be catastrophic. On the other hand, there is a risk of tampering with the conventional archiving methods because any party in a project can tamper with the data [7]. Therefore, this paper proposes to adopt blockchain technology in BIM archiving to address the two above-mentioned problems.

2.2. Blockchain in the AEC Industry

Different from conventional file systems or databases, blockchain utilizes a distributed data structure based on three key components: cryptographic algorithms, distributed databases, and decentralized consensus mechanisms [31]. Secure hash algorithms (SHA) are used to encrypt transactional data based on the agreed blockchain protocol so that it is practically impossible to retrieve the original data from the cipher text [9]. Through the distributed database and decentralized mechanism, all nodes of the file system collect transactions into a new block so that no third party is responsible for transaction validation and management [32]. In this way, the blockchain can achieve a secure and transparent archiving of digital data [33,34]. The advantages of using a blockchain for data storage include decentralization, security, transparency, immutability, and efficiency [35,36].

The blockchain is still in its early stages, and it will take many years before its potential can be fully explored. Currently, the most widely used way to classify blockchain generations has been proposed by Swan [37], who defined three generations of blockchain: (1) blockchain 1.0, which is mainly about currency; (2) blockchain 2.0, which focuses on contracts; and (3) blockchain 3.0, which further extends the scope to other applications beyond currency and finance. Blockchain 1.0 is the era of virtual currency represented by bitcoin, including its functions of payment and circulation [38]. Bitcoin outlines a grand blueprint that the future currency is no longer dependent on the release of central banks of each country but on the global currency unification. Blockchain 2.0 mainly focuses on smart contracts. Represented by Ethereum, smart contracts based on blockchain are programs that can self-execute when certain conditions are met [39]. When it comes to blockchain 3.0, the scope of applications can involve all aspects of a human's daily life. Instead of relying on a thirty to obtain trust or establish credit, blockchain 3.0 can improve the efficiency of the overall social system through the realization of trust [40,41].

In recent years, people from the AEC industry have also begun to make attempts to apply blockchain to different activities [12]. Several studies have been conducted to demonstrate the benefits and application modes of a blockchain in construction management [42–44]. Some people proposed implementing a blockchain in smart contracts of construction projects, which lies in the scope of blockchain 2.0 [45]. Similarly, Ahmadisheykhsarmast and Sonmez [46] developed a smart contract payment system for eliminating payment issues in the construction industry. Qian and Papadonikolaki [47] conducted semi-structured interviews to explore how thrust can be affected by a blockchain in supply chain management. Rodrigo et al. [48] developed a data model for blockchain-based embodied carbon estimation. Chong and Diamantopoulos [13] also implemented blockchain technology to improve the security of payment in construction projects. Besides contracts and payment, some researchers also apply blockchain to other applications, which can be classified into Blockchain 3.0. Dakhli et al. [49] conducted a case study about residential construction in which the total cost was reduced by 8.3% using blockchain deployment. A blockchain-enabled digital twin collaboration platform was developed for operations in modular integrated construction [50]. Wang et al. [51] proposed an information management system for a supply chain based on blockchain, which could improve information scheduling and traceability. Sheng et al. [52] utilized blockchain technology to develop a uniform and transparent system for managing quality information in the construction industry.

Some researchers also studied the integration of blockchain with BIM, theoretically discussing the potential and feasibility of applying blockchain to BIM data management [14,53]. The limited research that has practically integrated blockchain with BIM mainly focuses on finance and payment [13,54]. There are also a few researchers who have developed blockchain systems for BIM data storage and validated them with certain models. For example, a blockchain prototype was implemented for BIM data provenance using an Ethereum blockchain virtual machine [15]. A distributed common data environment was developed using blockchain and interplanetary file system (IPFS) for BIM-based design collaboration [16]. A confidentiality-minded framework for blockchain-based design has been developed, which can prevent unauthorized access to sensitive BIM data [17]. However, in order to practically utilize blockchain technology for archiving BIM data, the developed blockchain can be further improved by maintaining the independence of functional requirements and minimizing the information contents.

In summary, blockchain technology has the potential to improve the security and transparency of BIM data archiving. However, there are still limitations in the current studies on the integration of BIM with blockchain. Therefore, this paper utilizes an axiomatic design to develop a blockchain-BIM framework. Compared with previous studies on blockchain-BIM integration, this paper utilizes the axiomatic design approach to fully analyze the inner relationships among functional requirements and system contents. The developed framework can fully meet all functional requirements while minimizing the system complexity.

3. Methodology

Numerous researchers have employed systematic review methodologies to investigate various systems. However, within the existing literature, there is a noticeable absence of analogous approaches to the development of the proposed framework. Consequently, this study necessitates a design-oriented research methodology to effectively address this gap. Thus, the present research adopts an axiomatic design approach to formulate the conceptual framework for a digital archiving system of building information models leveraging blockchain technology. Axiomatic design, as defined by Suh [55], is a systematic system design approach utilizing matrix methods to analyze the conversion of customer needs into functional requirements (FRs), design parameters (DPs), and process variables (PVs). One of the primary advantages of employing the axiomatic design approach lies in its ability to generate innovative concepts for system research and development. Furthermore, this approach facilitates a reduction in random search processes, streamlining iterative trial and error procedures, clarifying design assessment principles, and empowering computational systems with creative capabilities [56]. Axiomatic design theory is based on two fundamental axioms: the independence axiom and the information axiom. In the context of identifying the characteristics of the proposed system, adherence to the independence axiom is paramount, ensuring that the requisite conditions of independence are satisfied. Subsequently, the information axiom will be utilized in future iterations to further refine the proposed system [57].

In order to facilitate the axiomatic design process, specific diagrammatic languages are employed. In this study, the Integrated Computer-Aided Manufacturing Definition for Function Modeling 0 (IDEF0) diagram is utilized to simplify the representation of the proposed system [58]. Integrated Computer-Aided Manufacturing Definition for Function Modeling (IDEF) [19] encompasses various techniques, with IDEF0 being one of them. IDEF0 utilizes the Structured Analysis and Design Technique (SADT) language to depict system functions. Figure 1 depicts a box diagram derived from the standard IDEF0 model. In this representation, boxes are employed to delineate proposed functions, while arrows signify the relationships between each box [58]. The adoption of IDEF0 aids in establishing the conceptual model of the proposed system framework.

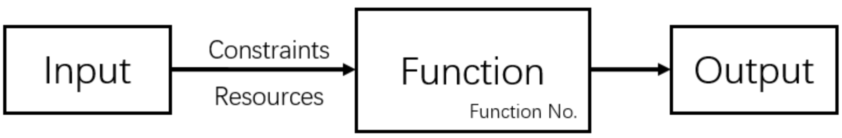

Figure 1. The box diagram for framework development.

Utilizing the devised framework, a blockchain platform, along with associated smart contracts, can be constructed using Hyperledger Fabric 2.4.4. Prior to uploading building information modeling (BIM) data onto the blockchain, it is imperative to convert the BIM model into the Industry Foundation Classes (IFC) file format for blockchain storage. Once the IFC data are uploaded onto a block, a corresponding block hash is generated, along with hashes of the data itself and the preceding block. To manage storage load efficiently, the IFC data may be distributed across multiple transactions within a block. Further comprehensive analysis regarding this process is provided in Section 5.

4. Framework Development

After the framework-formation process based on axiomatic design, five modules were designed (as shown in Figure 2).

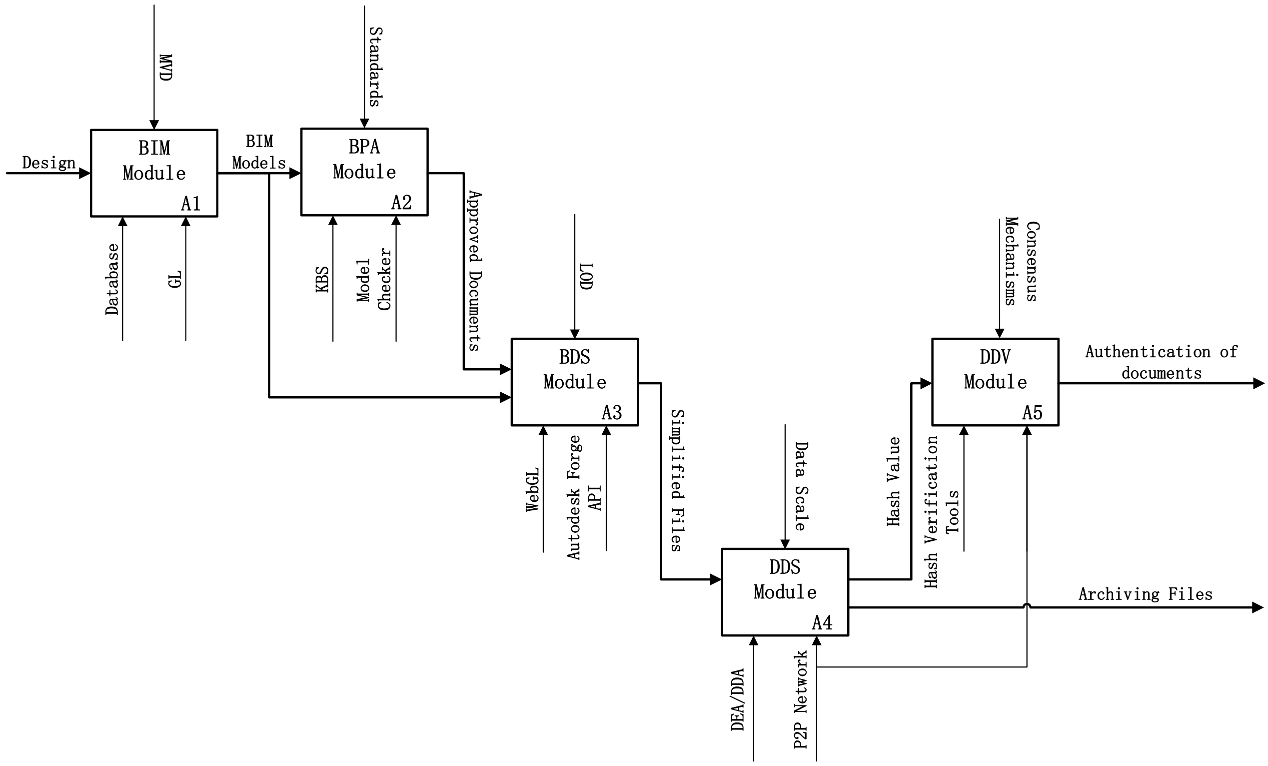

Figure 2. The blockchain framework for BIM data archiving.

(1) A1 Building Information Model (BIM) Module

In the design process, designers input their design work into Module A1, where they establish building information modeling (BIM) models. These models are subject to constraints imposed by Model View Definitions (MVD), which describe data exchange tailored to specific uses or workflows. Within Module A1, MVDs serve to pinpoint the data exchange requirements for recipients, aiding in the identification of necessary modifications. Modeling activities are facilitated through the utilization of both databases and Graphic Language (GL). Databases store information pertaining to design elements, while GL enables visualization of the 3D models. The output of Module A1 comprises BIM models, which subsequently serve as input for Module A2.

A1 module contains four levels of development:

a. Level 1—models

At this level, designers focus primarily on the development and refinement of BIM models, which encompass both 2D drawings and 3D elements, along with their associated properties. Collaboration among designers involves concurrent work on the same model, wherein modifications made to one view automatically propagate to corresponding views containing the same item. This real-time synchronization ensures consistency across multiple perspectives of the model. When a designer introduces changes to the models and synchronizes them with the central model, all other designers possessing the latest model version will promptly observe these modifications, fostering seamless collaboration and version control.

b. Level 2—participants

At this level, project participants work together to contribute to the BIM models. Project participants include design teams, clients, constructors, project managers, etc. BIM models are put on the cloud so that they can view the models on three ends: desktop app, web app, and mobile app. The constructors can use a tablet computer to manage the construction process on-site. Once they pull a request on a design change, the design teams will receive that request and take measures to adapt it.

c. Level 3—lifecycles

At this level, BIM models persist throughout the entire lifecycle of the project, from inception to operation. Initially established during the design phase, these models undergo optimization during the construction phase and are ultimately maintained during the operational phase. The Level of Detail (LOD) metric is employed to gauge the granularity of information contained within a BIM model. During the design stage, BIM models typically achieve LOD 300, providing a foundational level of detail. As the project progresses to the construction phase, additional details are incorporated into the models, often reaching LOD 400 to meet the requirements of the construction process. Upon completion of construction, an as-built BIM model, typically achieving LOD 500, is delivered to operators. This comprehensive as-built model encompasses all facets of the building, enabling operators to effectively manage the maintenance process. Subsequent updates to the model occur as component replacements take place, ensuring that the BIM model remains accurate and reflective of the building's current state throughout its operational lifespan.

d. Level 4—communities

At this level, BIM models originating from diverse projects are consolidated within a community-based platform, enabling comprehensive analysis and collaboration across multiple projects. Such a platform facilitates influence analysis among various projects, aiding in conflict resolution and enhancing overall project coordination. Commonly, Geographic Information Systems (GIS) serve as the foundational platform for integrating and managing these diverse BIM models. GIS platforms are adept at gathering, organizing, and analyzing spatial data, making them well-suited for handling the complex spatial relationships inherent in BIM models. By incorporating BIM models into GIS, conflicts between models from different projects can be efficiently resolved.

However, the utilization of 3D GIS introduces challenges, particularly concerning hardware capacity and system performance. Integrating a community of BIM models can strain the resources of the GIS platform, potentially leading to performance degradation. To address this issue, lightweight versions of BIM models are essential for alleviating the workload on the GIS platform, ensuring optimal system performance while maintaining the integrity of the integrated BIM data.

(2) A2 Building Plan Approval (BPA) Module

It is necessary to have a building plan approval process before construction can commence. A2 BPA module is used to approve building plans. Designers input BIM models into the A2 BPA module. The reviewers should check whether the BIM models are following the standards. A Knowledge-Based System (KBS) is used by the building plan designers to revise their design. KBS is an expert system that reasons and uses a knowledge base to solve complex problems. Building plan designers utilize KBS to reason appropriate problems that may not meet the requirements and update their BIM models based on the results. A model checker is used to check how the models meet the requirements. Once the BIM models meet all the requirements, the approved documents will be output to the A3 module.

A2 BPA module contains two levels of development:

a. Level 1—2D documents

At this level, BIM models are transformed into 2D documents. Plans, sections, and details are exported from BIM software. BIM models are patterned in 2D. Appropriate authorities review the submitted 2D documents and provide feedback to the building plan designers. The building plan designers revise the BIM model and export the 2D documents again for resubmission. This is the ordinary process of getting the building plan approved. The authorities are skilled in reviewing 2D documents. However, this process is not efficient enough, as the 2D documents have to be exported when they need to be submitted.

b. Level 2—digital

At this level, digital BIM models are directly integrated into the building plan approval process, revolutionizing traditional review methods. BIM software empowers reviewers to effortlessly identify conflicts across various disciplines within the models. Plans, sections, and detailed components are comprehensively represented within the BIM environment, providing reviewers with a holistic view of the project. Reviewers leverage BIM models to assess compliance with established standards, scrutinizing all drawings embedded within the model to ensure regulatory adherence. Additionally, reviewers can annotate and provide feedback directly within the BIM environment. Building plan designers incorporate these comments into revisions, resulting in a streamlined and collaborative review process. This digital approach offers significant efficiency gains compared to traditional methods. However, challenges arise from less experienced reviewers and uncertainties surrounding digital approval processes. Addressing these challenges through training initiatives and clear procedural guidelines is essential to fully realize the benefits of digital building plan approval.

(3) A3 Building Data Simplification (BDS) Module

To address the challenge of presenting large BIM models, the A3 Building Data Simplification (BDS) module is introduced. This module serves to simplify and visualize building data for enhanced accessibility. Building plan reviewers input approved documents from the A2 module, while building plan designers input BIM models from the A1 module. The A3 module leverages Web Graphics Library (WebGL) technology and integrates the Autodesk Forge Application Programming Interface (API) to develop a 3D visualization platform. Utilizing these tools, the module simplifies BIM models according to LOD specifications. Additionally, it incorporates approved documents into the BIM models, enhancing contextual understanding. When users select a specific plan, scanned approved documents are dynamically attached to provide additional context. The simplified BIM models and associated documents are then transmitted to the A4 module for further processing. Notably, the original BIM models and approved documents remain included within the simplified files, ensuring comprehensive data preservation and accessibility throughout the workflow.

A3 BDS module contains two levels of development:

a. Level 1—stand-alone

At this level, the building data simplification process is performed in a stand-alone application. Such an application can provide an overview of all the BIM models and their approved documents in a simplified mode. Models are optimized by reducing the number of triangular. The risk of data loss in this stand-alone application is extremely high as no building data are stored in other devices. All BIM models and their attachments are operated in a stand-alone device. However, this process is not efficient, as it has high requirements for the operating device. The operating device has to load the whole BIM model on its desktop, which always causes crashes on the computers.

b. Level 2—cloud-based

At this level, building data are stored in cloud repositories and accessed through web browsers, offering convenient and widespread accessibility. To ensure efficient data delivery, BIM models are optimized and converted into smaller-scale formats, facilitating seamless transmission over internet connections. A dedicated cloud server, equipped with high-standard configuration, hosts all the building models, ensuring robust performance and reliability. Users can access the building data, including BIM models and associated documents, via web browsers from any location with internet connectivity. However, the increased workload for web browsers poses a challenge for users, necessitating browser capabilities to effectively handle and present the comprehensive building data. One advantage of storing data in the cloud is the reduced risk of data loss or corruption, as the models are securely hosted on cloud servers with appropriate backup and security measures in place. This mitigates concerns regarding data integrity and enhances the overall reliability of the system.

(4) A4 Distributed Data Storage (DDS) Module

In the A4 DDS module, developers upload simplified files onto a Peer-to-Peer (P2P) network, leveraging blockchain technology for data integrity verification. The module computes hash values for each file, serving as unique identifiers for file originality verification. Subsequently, the A4 DDS module archives the files and forwards the generated hash values to the A5 Data Distribution Verification (DDV) module. When users require access to specific files, they input corresponding hash values into the A5 DDV module. The A4 DDS module then retrieves the archived files associated with the provided hash values for distribution. Concurrently, the A4 DDS module divides each simplified file into 30 fragments, duplicates them, encrypts the duplicates using a data encryption algorithm (DEA), and disperses them across the P2P network. Notably, any subset of 10 fragments from the dispersed duplicates is sufficient to fully reconstruct the original file. Upon user request, retrieving any 10 fragments from the P2P network enables file recovery, followed by decryption using a data decoding algorithm (DDA) to restore the original content. This decentralized and redundant distribution mechanism ensures data safety, integrity, and robustness against potential network disruptions or data loss incidents.

A4 DDS module contains two levels of development:

a. Level 1—centralized

At this level, building data are stored in a centralized way. All files are stored in a centralized server, and the users can obtain the files by accessing the centralized server from the desktop. This process is efficient as all the users can access the building data without storing the building data. However, data safety becomes the biggest challenge for this process. Once the data center breaks down, all the data will be lost. Meanwhile, the owners of the data center can modify the building data if they want to. This makes the building data untrustworthy and faces the risk of data tampering.

b. Level 2—distributed

At this advanced stage, building data are securely maintained in a distributed manner across a P2P network. This decentralized approach significantly reduces the risk of a single point of failure and greatly enhances data safety. In the event of node failures within the P2P network, the remaining nodes are capable of recovering the file, ensuring data availability and resilience. Furthermore, this distributed architecture eliminates the possibility of unauthorized file modification by third parties. Prior to transmission to the P2P network, files are encrypted using advanced encryption technology. Only authorized users possess the decryption keys required to access and recover the files. This ensures that only the rightful user can decrypt and access the content. Leveraging blockchain technology, the hash value of the original file is recorded and stored securely. When users request access to a file, the hash value is utilized to verify the authenticity and integrity of the file, ensuring that it has not been tampered with or modified since its creation. The digital-archiving process, based on blockchain and distributed P2P network technology, is depicted in Figure 3, highlighting the robustness and security measures inherent in the system.

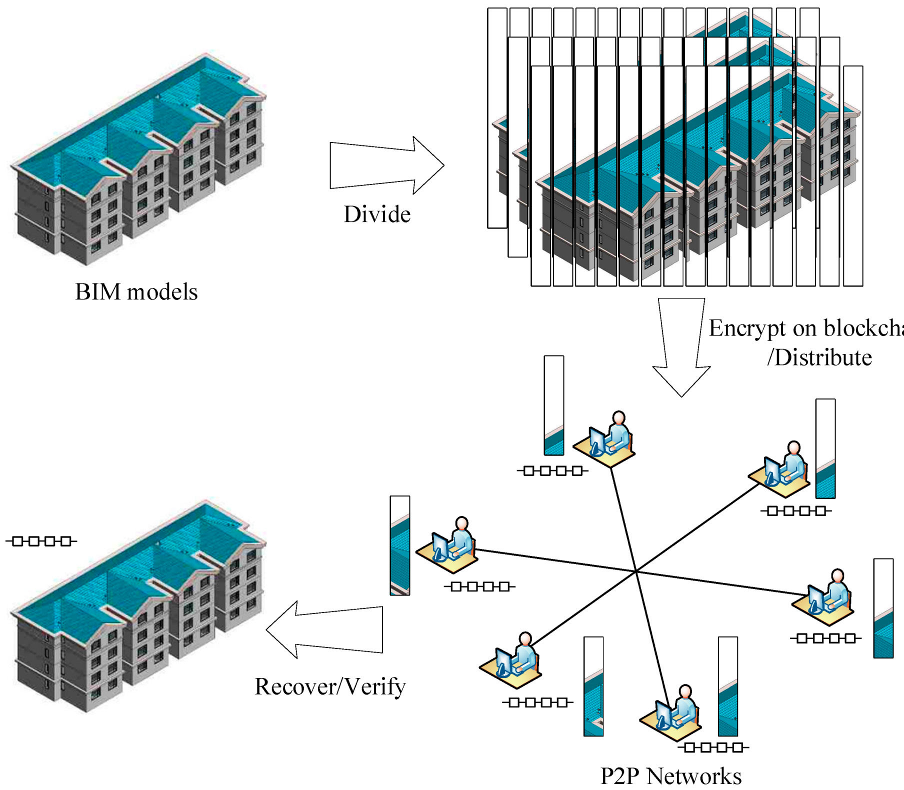

Figure 3. Digital-archiving process based on blockchain.

(5) A5 Digital Document Verification (DDV) Module

When the users store a file in the A4 DDS module, they will input a hash value into the A5 DDV module. A5 DDV module is working based on consensus mechanisms. It has hash verification tools to verify the hash values. A P2P network is available for this process. Once the hash values are verified, the A5 DDV module will output the authentication of documents.

A5 DDV module contains two levels of development:

a. Level 1—password-based

At this level, the digital document verification process is based on the password. The data safety is low for this process as the system operator can modify the password. The problem of this process is similar to the one of centralized data storage as the third party can modify the data. By using this password-based digital document verification system, the users can verify the originality of the file stored in the A4 module. However, the originality is limited to third-party modification.

b. Level 2 Blockchain-Based

At this level, data safety is highly guaranteed as the authentication information is stored in the block. Only the right hash value can verify that the document is original. The simplified files are stored in the A4 module and the A4 DDS module will send the hash value of the file to the A5 DDV module. When the A5 DDV module receives the hash value, it will record the hash value in the blockchain. When the users need to get the file from the system, they will use the hash values from the A5 DDV module to verify whether the file has been modified. This process can make sure that the third party cannot modify any file in the system.

This paper applies the axiomatic design to analyzing the inner relationships among functional requirements and system contents. In order to minimize the blockchain system complexity while fully meeting all functional requirements, the proposed framework is verified by the independence axiom. To maintain the independence of the proposed system, the main function requirement has been divided into five function requirements (FRs). For the main function requirement, a design parameter (DP), a building information model digital archiving system (BIM-DAS), was made to adapt. Meanwhile, the main DP has also been made into five divisions. The main constraint (C) of the proposed system lies in interoperability. Provided that, this constraint has also been made into five divisions for the five FRs (see Table 1). To establish BIM models based on design documents, they need a BIM module with the constraint of MVD. To approve building plans before pursuing the construction business, they need a BPA module with the constraint of standards. To simplify building metadata and visualize it via a web interface, they need a BDS module with the constraint of LOD. To store digital construction documents in a distributed manner, they need a DDS module with the constraint of data scale. To verify the genuineness of digital construction documents obtained from the P2P network, they need a DDV module with the constraint of consensus mechanisms.

Table 1. The divisions of FRs and DPs and Cs.

Factors	Contents	Divisions
FR_0	To archive digital construction documents	FR_1: To establish BIM models based on design documents FR_2: To approve building plans before pursuing the construction business FR_3: To simplify building metadata and visualize via web interface FR_4: To store digital construction documents in a distributed manner FR_5: To verify the genuineness of digital construction documents obtained from the P2P network
DP_0	BIM-DAS	DP_1: A1 BIM Module DP_2: A2 BPA Module DP_3: A3 BDS Module DP_4: A4 DDS Module DP_5: A5 DDV Module
C_s	Interoperability	C_1: MVD C_2: Standards C_3: LOD C_4: Data Scale C_5: Consensus Mechanisms

The relationship between different FRs and DPs within the proposed framework is elucidated through a systematic mapping, as presented in Table 2. Specifically, FR2 and FR3 are intricately linked with DP1, which pertains to BIM models. This linkage stems from the A1 BIM module responsible for inputting BIM models into both the A2 BPA module and the A3 BDS module. Meanwhile, FR3 exclusively correlates with DP2, associated with approved documents, as evidenced by the A2 BPA module's input of approved documents into the A3 BDS module. Additionally, FR4 is intimately tied with DP3, which concerns simplified files, given that the A3 BDS module inputs such files into the A4 DDS module. Lastly, FR5 demonstrates a direct correspondence with DP4, involving hash values, with the A4 DDS module responsible for inputting hash values into the A5 DDV module. These mappings unveil the interdependencies and interactions between various FRs and DPs, delineating the data flow and operational processes across different modules within the framework.

Table 2. Mapping between FRs and DPs for BIM-DAS.

FR_s	**DP_s**				
	DP_1	**DP_2**	**DP_3**	**DP_4**	**DP_5**
FR_1	Self-Interaction	Independent Operation	Independent Operation	Independent Operation	Independent Operation
FR_2	BIM Models	Self-Interaction	Independent Operation	Independent Operation	Independent Operation
FR_3	BIM Models	Approved Documents	Self-Interaction	Independent Operation	Independent Operation
FR_4	Independent Operation	Independent Operation	Simplified Files	Self-Interaction	Independent Operation
FR_5	Independent Operation	Independent Operation	Independent Operation	Hash Value	Self-Interaction

Based on the mapping between FRs and DPs, the design structure matrix (DSM) for the proposed system has been given as follows:

$$\begin{vmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 & 0 & 0 \\ X & X & 0 & 0 & 0 \\ X & X & X & 0 & 0 \\ 0 & 0 & X & X & 0 \\ 0 & 0 & 0 & X & X \end{vmatrix} \begin{vmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \end{vmatrix} \quad (1)$$

Equation (1) is a quasi-coupled matrix that meets the requirements of the Independent Axiom. Hence, the proposed system is functionally independent.

5. Illustrative Example

This paper validates the proposed blockchain approach using a test environment consisting of a VMware Workstation Pro 17 virtual machine with 8 GB of RAM and a 130 GB hard disk. The virtual machine utilizes Ubuntu 22.04 as the operating system. Four dockers were installed in the virtual machine to separate different blockchain peers. Hyperledger Fabric 2.4.4 was deployed to build the blockchain network. The Hyperledger Explorer and the Caliper were configured to view transaction details and test the latency of the built blockchain network. We tested the latency and throughput of the constructed blockchain network using the Caliper testing tool, and the results are shown in Figure 4. When considering the latency performance of the blockchain network, we found that the uploading of 5000 transactions only incurred a tiny latency of 0.09 s on average. For the 30,667 query transactions, the average latency was almost zero, and these latencies are so small that they can be regarded as insignificant. In terms of throughput, the network is able to set 65 transactions and query 1057.2 transactions per second, which is sufficient for common work scenarios.

Caliper report

Summary of performance metrics

Name	Succ	Fail	Send Rate (TPS)	Max Latency (s)	Min Latency (s)	Avg Latency (s)	Throughput (TPS)
Set value.	5000	0	66.8	2.02	0.02	0.09	65.0
Query value.	30667	0	1057.3	0.02	0.00	0.00	1057.2

Figure 4. Latency and throughput of the blockchain network.

This study takes a simple BIM model as an example for illustration. The model was created using Autodesk Revit 2020, containing 240 components and around 11,000 lines of contents in the corresponding Industry Foundation Classes (IFC) file (as shown in Figure 5).

We upload the corresponding data in the IFC model to the blockchain to verify the compatibility of the archiving method. Figure 6 shows the browser page of the corresponding blockchain built in this paper, which shows some specific information of the blockchain in detail, such as the block height of the blockchain, the nodes of the blockchain, and the number of chain codes.

By uploading the information in the IFC file to the blockchain network, the corresponding block hash is generated, along with the hash of the data and the hash of the previous block, as shown in Figure 7.

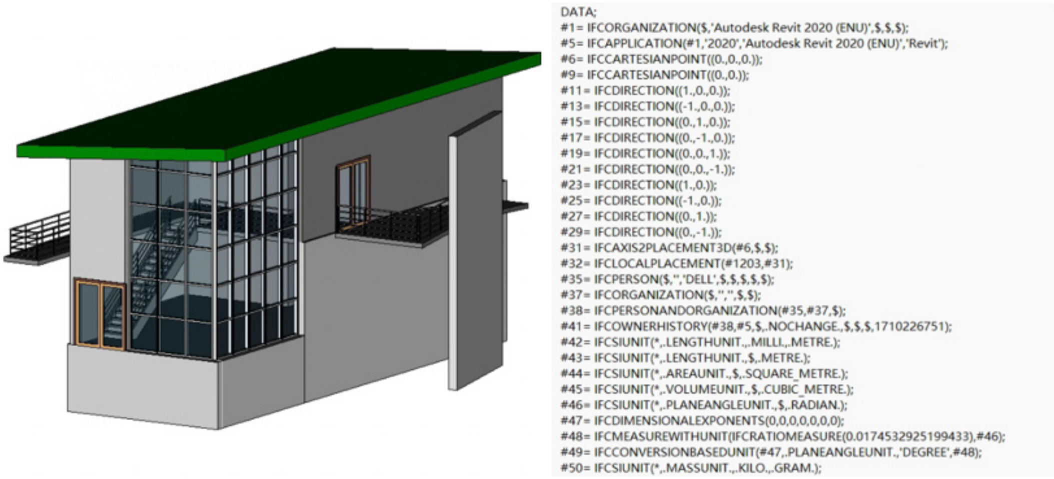

Figure 5. The BIM model and corresponding IFC data of the illustrative example.

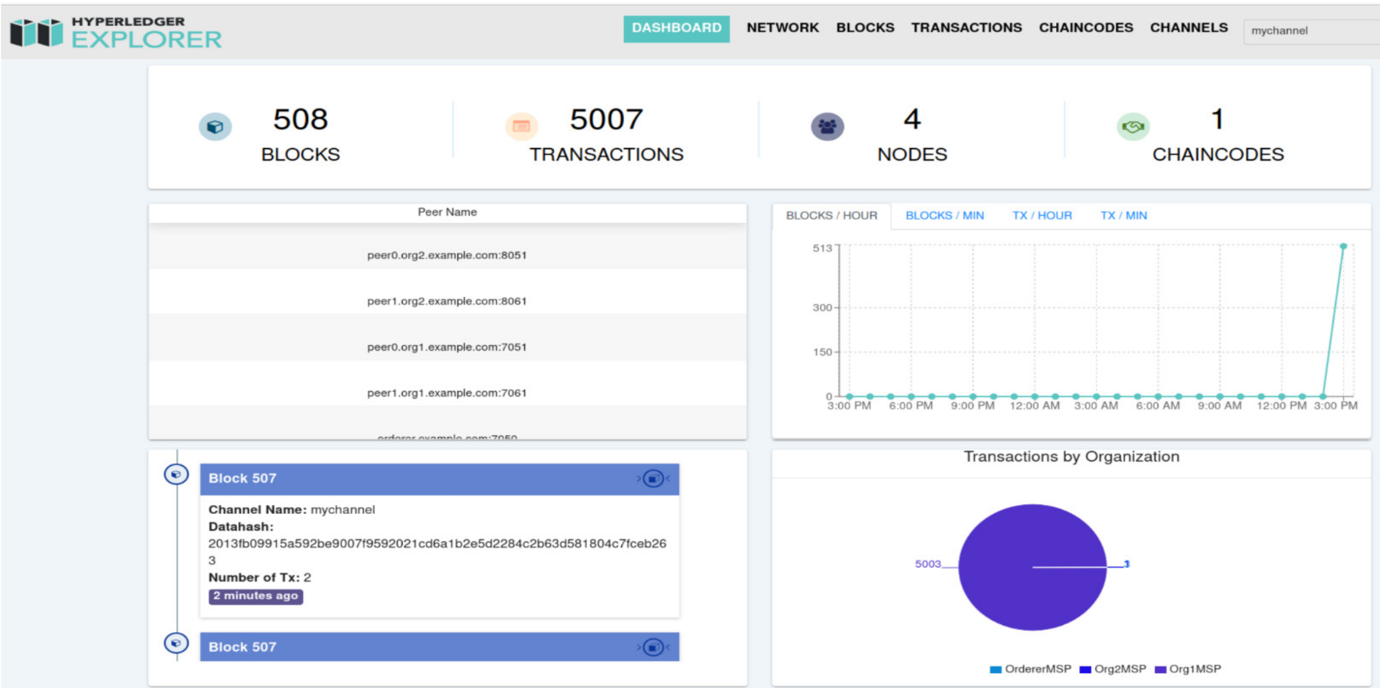

Figure 6. Blockchain-based BIM model archiving with distributed storage.

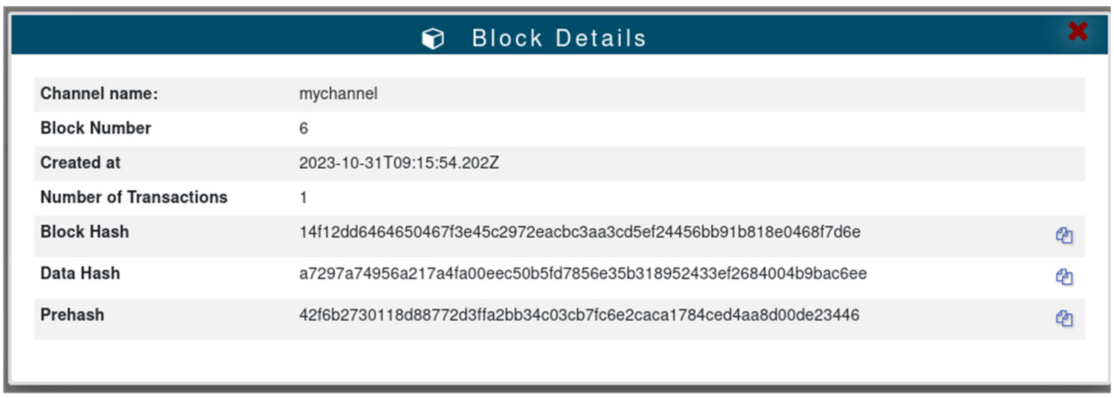

Figure 7. Block details of the IFC data.

The uploaded IFC data contain a wealth of relevant information. For example, #815=IFC-COLUMN indicates its line number and component type. "21HtZ13c2IGvOY9rRYV9G5" is the GlobalId of the column, and #140005 refers to the history of modifiers creating and modifying the column. Since the IFC file needs to be modified by multiple users (e.g., construction engineers and mechanical analysts) with corresponding node information, the subsequent related parameters are not repeated. The specific uploaded information is shown in Figure 8. As tested with the BIM model, each transaction can store over 5000 lines of IFC contents, and 1 block can have 10 transactions. Therefore, each block on the blockchain can store over 50,000 lines of IFC content. If a BIM model is too complicated, the IFC contents have to be distributed on multiple blocks of the blockchain.

Figure 8. Details of the uploaded IFC data.

6. Discussion

For the A1 BIM module, FR1 is to establish BIM models based on design documents, and C1 is MVD. A1 BIM module contains four levels of development: models, participants, lifecycles, and communities. At Level 1 models, the designers concentrate on models that contain 2D drawings, 3D elements, and properties. At Level 2—participants, project participants, including design teams, clients, constructors, and project managers, work together to contribute to the BIM models. At Level 3—lifecycles, BIM models are kept throughout the whole lifecycle. At Level 4—communities, BIM models from different projects are integrated into a community-based platform, and influence analysis is conducted among different projects.

For the A2 BPA module, FR2 is to approve building plans before pursuing the construction business, and C2 is the standard. The A2 BPA module contains two levels of development: paper-based and digital. At Level 1—paper-based, BIM models are transformed into 2D paper-based documents. At Level 2—digital, BIM models are directly used in the building plan approval process.

For the A3 BDS module, FR3 is to simplify building metadata and visualize them via a web interface, and C3 is LOD. The A3 BDS module contains two levels of development: stand-alone and cloud-based. At Level 1—stand-alone, stand-alone applications can provide an overview of all the BIM models and their approved documents in a simplified mode. At Level 2—cloud-based, building data are stored in the cloud and presented via browsers.

For the A4 DDS module, FR4 is to store digital construction documents in a distributed manner, and C4 is the data scale. The A4 DDS module contains two levels of development: centralized and distributed. At Level 1—centralized, all the building data are stored in a centralized server, and the users can access the files by accessing the centralized server from a desktop. At Level 2—distributed, building data are stored in the P2P network in a distributed manner.

For the A5 DDV module, FR5 is to verify the genuineness of digital construction documents obtained from the P2P network, and C5 is consensus mechanisms. The A5 DDV module contains two levels of development: password-based and blockchain-based. At Level 1—password-based, the digital document verification process is based on a password, and data safety is limited to third-party modification. At Level 2—blockchain-based, the authentication information is stored in the block, and the data safety is high.

The significance of this research is to verify the compatibility and feasibility of blockchain technology for archiving building information models. Using Hyperledger Fabric 2.4.4 as a tool, we can ensure the authenticity and integrity of building information in the distributed network by uploading the information in the IFC file. Through this experiment, we can conclude that blockchain technology can be successfully applied to the archival verification of building information models. By uploading the information in the IFC file, we can not only ensure the credibility of the archived data but also realize the traceability of the data and the checking of historical information. In addition, the security and reliability of the data can be ensured through distributed storage. Although this study uses a simple building information model as an example for validation, the method has wider applicability. Building information models in any region or industry can likewise be archived and verified by this method to improve the credibility and security of the data. Compared with existing blockchain-based BIM data-archiving studies, the framework proposed in this paper utilizes the axiomatic design approach to fully analyze the inner relationships among system contents and functional requirements. The developed framework can minimize blockchain system complexity while fully meeting all functional requirements.

Future research can further explore the application of blockchain technology in BIM collaboration. For example, research can be conducted on how to share and collaborate building information on the blockchain to facilitate cooperation and communication among parties. Through these studies, we can further improve the management and protection mechanisms of building information models to promote the digital transformation and innovative development of the construction industry.

7. Conclusions

The integration of BIM with blockchain is attracting increasing attention in the AEC industry. In order to utilize blockchain technology practically for archiving BIM data, this study aims to develop a blockchain system framework that can maintain the independence of functional requirements and minimize the information contents. A BIM-DAS framework is proposed to archive BIM data in IFC format. To meet the requirements of the independence axiom of the axiomatic design approach, this study divides the proposed system framework into five modules, including the BIM module, building plan approval (BPA) module, building data simplification (BDS) module, distributed data storage (DDS) module, and digital document verification (DDV) module. The framework is verified by the independence axiom and is proved to be functionally independent. A blockchain system is developed based on the proposed framework using Hyperledger Fabric and a simple BIM model is taken to validate the system. The results show that each transaction of a blockchain can store over 5000 lines of IFC contents with 0.09 **s** of uploading latency, indicating the feasibility and efficiency of the proposed blockchain archiving approach.

We aim to improve the efficiency and security of BIM data-archiving methods based on blockchain technology, thereby enhancing their practical application value. At the same time, we use typical cases to verify the functionality and efficiency of this archiving method. The findings of this study suggest that the proposed system is capable of digitally archiving BIM models in the AEC industry. This paper provides an effective reference for the application of blockchain technology in the construction industry, guides the integration of BIM with blockchain technology, and provides strong support for the wider application of BIM. However, this study is limited by the lack of multi-user collaboration. In future studies, research can be conducted on how to share and collaborate building information on the blockchain to facilitate cooperation and communication among parties.

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List of Abbreviations

AEC	Architecture, engineering, and construction.
API	Application Programming Interface.
BDS Module	Building Data Simplification Module.
BIM Module	Building Information Model Module.
BIM-DAS	Building information model digital archiving system.
BPA Module	Building Plan Approval Module.
DDA	Data decoding algorithm.
DDS Module	Distributed Data Storage Module.
DDV Module	Digital Document Verification Module.
DEA	Data encryption algorithm.
DP	Design parameter.
FR	Functional requirement.
GIS	Geographic Information System.
GL	Graphic Language.
KBS	Knowledge-Based System.
LOD	Level of Detail.
MVD	Model View Definitions.
P2P	Peer to Peer.
SOP	Security of payment.

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