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BIM Collaborative Design & Building Operation Management with Hashgraph Support

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Abstract

With the increasing complexity of building functionality requirements, the number of design professionals involved in construction projects has also grown. In traditional design processes, information transfer errors often lead to disjointed design plans. Therefore, this study proposes a model for Building Information Modeling collaborative design and building operation management based on Hashgraph. The experimental results show that the proposed model achieved a consensus accuracy of up to 95.3% and a throughput of 120 bytes per second. Under various conditions, its accuracy and throughput were about 10-25% higher than the advanced model. Additionally, in the actual project design plan, the optimization rate of the total cost compared to the maximum cost is 12.14%, and the operation and maintenance cost savings per year reach 4.3 million yuan. The above results indicate that the research method effectively solves the problem of the lack of efficiency and accuracy in the construction engineering design process method, which relies on two-dimensional drawings as the core, relies on phased linear delivery, and manual coordination, and helps to promote the development of the intelligent construction industry.

Keywords: Hashgraph; Building information modeling; Collaborative design; Operation and maintenance management; Information transfer.

1. Introduction

Building Information Modeling (BIM) has become the cornerstone of the construction industry, and its visual and collaborative characteristics have profoundly changed the design and management models. However, with the increasing complexity of projects and the deepening requirements for complete lifecycle management, the architectural bottlenecks of traditional BIM systems in terms of ‘collaborative trust’ and ‘real-time information synchronization’ are becoming increasingly prominent [1, 2]. Currently, the traditional design process suffers from disjointed design stages, leading to information transfer errors. These errors are often discovered during construction, prompting a temporary change to the design plan and delaying project progress [3]. Therefore, how to efficiently and accurately synchronize design information to the participants has become a hot research topic. With the advancement of information technology, the emergence of Building Information Modeling (BIM) has driven the development of collaborative design. As a new structural design model in the field of construction, BIM excels in visualizing and synchronizing information transfer [4]. Hashgraph, on the other hand, enables data synchronization and consensus with minimal computing resources, ensuring consistency of information across different parts [5].

Based on this, a BIM collaborative design, operation, and maintenance management model based on Hashgraph is studied and constructed. By introducing a reputation mechanism and a leader election algorithm, the efficiency of information synchronization and system security is enhanced, providing a new technical path for intelligent collaborative design in the construction industry. In addition, the collaborative design, operation, and maintenance management of construction projects can essentially be regarded as a kind of manufacturing process. The issues involved, such as multidisciplinary collaboration, resource scheduling, cost control, and information synchronization, are closely related to the optimization of production systems, supply chain collaboration, and process management in industrial engineering. This makes the proposed model in this study not only applicable to construction engineering but also efficient, with its consensus, dynamic reputation management, and real-time synchronization mechanism providing references for distributed collaboration, real-time production scheduling, and complete life-cycle management in industrial manufacturing systems. The objective of the research is to address the shortcomings of existing digital solutions, such as the traditional BIM collaborative platform’s reliance on centralized servers, which poses a risk of a single point of failure, and the lack of cross-organizational data sovereignty and trust mechanisms. Mechanisms such as Proof of Work (PoW) consume huge amounts of computing resources. The transaction processing speed is difficult to meet the high-frequency and fine-grained BIM collaboration requirements. The main contributions of the research are as

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follows. First, a quantified trust computing model suitable for multi-party collaboration in the fields of architecture, engineering and construction was proposed, mapping the behavior of nodes into dynamically updatable reputation values, providing a computable method for solving the problem of “trust deficiency” in projects. Second, a theoretical framework of “reputation-driven consensus” has been developed, combining a traditional distributed consensus mechanism with domain-specific collaborative logic to reveal how the reputation mechanism affects consensus efficiency and collaboration outcomes, and to promote the theoretical development of decentralized consensus in resource-constrained engineering scenarios. Thirdly, through case studies, the effectiveness of the research method in addressing classic building management issues such as “information silos” and “inefficient change management” was verified, enriching the theoretical toolbox of building informatics.

2. RELATED WORKS

BIM, as an emerging building structure design optimization technology, enables collaborative design with designers and demonstrates effective design ideas to achieve cost reduction and efficiency improvement [6]. Many scholars both domestically and internationally have conducted research on this topic. Jerushan et al. found that in the field of AEC (Architecture, Engineering and Construction), BIM is developing rapidly, among which integrating the point cloud of 3d laser scanners with BIM is an effective solution. Subsequently, the article summarizes various applications throughout the entire building life cycle [7]. Naghibalsadati et al. analyzed the evolving research prospects of promoting sustainable construction and demolition waste management practices through BIM technology, and conducted a comprehensive text mining analysis of 493 academic publications from January 2009 to February 2024 using the PRISMA framework. Co-occurrence analysis reveals three main research topics: (1) using digital twins and prefabrication to reduce waste, (2) integrating environmental impact assessment, and (3) data-driven decision-making [8]. However, the existing BIM collaborative applications still generally face the following challenges: First, most systems rely on a centralized server architecture, which poses a risk of single point of failure and makes it difficult to support cross-organizational, high-concurrency real-time collaboration; Second, information synchronization is mostly based on file exchange or centralized databases, with frequent version conflicts and a lack of a reliable process traceability mechanism. Thirdly, the problem of information disconnection between the design and operation and maintenance phases remains prominent, and the “information island” phenomenon has not been fundamentally resolved, resulting in the need for a large amount of manual verification and data reconstruction during the operation and maintenance phase.

The Hashgraph consensus algorithm overcomes the problem of wasted computing resources through decentralization. Researchers at home and abroad have effectively solved many existing problems by fully utilizing this algorithm. Wang’s team, addressing the high computational costs of traditional consensus mechanisms used in vehicle-to-vehicle energy trading, proposed a Hashgraph-based consortium consensus mechanism. Experiments demonstrated that this mechanism has excellent performance and practicality in vehicle-to-vehicle energy trading [9]. Wang et al., addressing the issue that traditional consensus algorithms are not suitable for applications that require real-time services such as energy trading, proposed a Hashgraph-based consortium consensus mechanism. Experiments confirmed the high efficiency and security of this mechanism in a blockchain-based vehicle-to-vehicle energy trading platform [10].

In addition, with the booming development of the construction industry, collaborative design and operation management of buildings have become typical optimization problems in the industry. Scholars from various countries have conducted research and proposed different solutions to these issues. For example, Xiao’s team, addressing the lack of BIM application in prefabricated building design, proposed a BIM-based PCP collaborative design conceptual model to determine the accuracy of BIM in different design stages. The results showed that the effectiveness of the BIM-based collaborative design method was verified through practical examples [11]. Bao et al., addressing the issue of low efficiency in traditional interior design and construction delivery, proposed a new industry concept, “Manufacturing and Assembly Design.” The study showed that this concept improves productivity, and its collaborative effect with interior design and construction provides a new model for interior designers and off-site practitioners [12]. Wei’s team, addressing the limitations of current smart building operation and maintenance methods, proposed an intelligent building operation system for information resource sharing and management. By improving work efficiency and providing a comfortable working environment, it reduces the number of managers while saving energy, offering an efficient, convenient, and reliable management solution [13]. Akinradewo et al., addressing the issue that BIM is widely used in the construction industry but often misunderstood and underutilized, proposed promoting the application of BIM in the maintenance and management of infrastructure in the construction industry. The results of this study are valuable for facility managers and stakeholders, as they provide insights into the implementation of BIM in this sector [14]. Valinejadshoubi’s team, addressing the maintenance issues related to the lack of detailed visual information about completed facilities and large-scale sensor deployments, proposed a BIM-based system architecture. The study showed that the developed system can help facility managers take timely actions in case of sensor failures, ensuring minimal disruption to monitoring services [15]. Although consensus mechanisms have been widely applied in distributed systems, their direct transplantation into BIM collaborative scenarios still faces significant obstacles: Firstly, traditional consensus mechanisms are primarily oriented towards financial or Internet of Things transaction scenarios, without accounting for the multidisciplinary, cross-stage, and long-cycle characteristics of engineering collaboration. Secondly, the current mechanism lacks dynamic assessment and incentives for the behaviors of participants, and thus cannot effectively suppress the behaviors of malicious nodes. Finally, the performance of most consensus algorithms is unstable in non-ideal environments such as dynamic node joining/exiting and fluctuating network latency, making it difficult to support the complex collaboration requirements of actual engineering projects.

To sum up, although existing research has made significant progress in the collaborative design, operation, and maintenance management of buildings, it still faces significant challenges. Specifically, first, there is a disconnection between the application of technology and the demands of the field. The application research of Hashgraph has not fully considered the collaborative logic and business rules in the fields of architecture, engineering, and construction. The second issue is the absence of a trust mechanism. Existing BIM collaborative optimization schemes fail to introduce a quantifiable, computable trust model to regulate participants' behavior. The third issue is the lack of an integrated architecture that can simultaneously achieve efficient information synchronization, trusted node governance, and secure decision-making consensus. Therefore, it is feasible to study the introduction of BIM technology and the Hashgraph consensus algorithm into the collaborative design and operation and maintenance management of buildings. This can improve the efficiency and applicability of collaborative design and operation and maintenance management for buildings, thereby meeting the intelligent collaborative design and operation and maintenance management needs of the construction industry. The core contribution of the research lies in designing a dynamic leader election algorithm that is linked to the reputation mechanism to meet the security requirements of project decision-making. At the same time, it verifies the effectiveness of this framework in enhancing collaborative efficiency and reducing project costs and operational and maintenance expenses from both theoretical and experimental perspectives.

3. CONSTRUCTION OF BIM AND ITS COLLABORATIVE DESIGN MODEL BASED ON HASHGRAPH

3.1. BIM design based on Hashgraph

BIM, as an emerging concept and technology, plays a significant role in core aspects of building collaborative design, engineering construction, cost control, and post-construction operation and maintenance management, thanks to its characteristics such as visualization and parametric design [16]. However, its data processing capability is relatively weak, and when facing a large amount of building information parameters, it requires significant time, leading to a decrease in the efficiency of information transmission. This results in the inability to synchronize information with all design personnel in a timely manner, thus affecting project progress. Therefore, a method capable of synchronously processing information is needed in combination with BIM. Hashgraph is an efficient distributed consensus algorithm that can synchronize data and achieve consensus with minimal computational resources, offering excellent features such as high throughput and fault tolerance. Its algorithmic workflow is shown in Figure 1 [17].

As shown in Figure 1, the Hashgraph system includes four nodes: A, B, C, and D. When node C randomly transmits all the information it knows to node D, node D stores all the events it is unaware of into its local Hashgraph based on the same data structure. Node D then records the new event "d4," which includes the hash value of the event "d3" that occurred most recently to it, as well as the hash value of node C's latest event "c2." At the same time, node D records the timestamp and some transaction information that has not been included in the Hashgraph into the event "d4." Following this pattern, each node repeatedly cross-searches for another node and informs the other of all the unknown events. The time required for information propagation across different nodes during this process is shown in Equation (1).

$$R=\log_{f+1}(n)+\frac{1}{f}\log(n)+O(1) \tag{1}$$

In Equation (1), n represents the total number of nodes, f represents the number of other nodes, R represents the number of propagation rounds, and $O(1)$ represents the propagation time of the first node. In summary, Hashgraph not only records all the events that occur but also retains the historical records of all the events exchanged between nodes. Although the Hashgraphs of each node differ, they can all accurately record the events created by the respective nodes. However, Hashgraph has some issues, such as being susceptible to the negative influence of nodes and lacking stability. Therefore, the study introduces a reputation model aimed at regulating node behavior and encouraging nodes to maintain a positive attitude during the information synchronization process. The Hashgraph with the reputation model is shown in Figure 2.

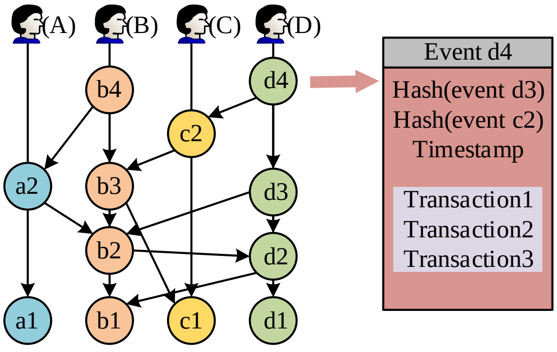


Figure 1. Hashgraph application flowchart

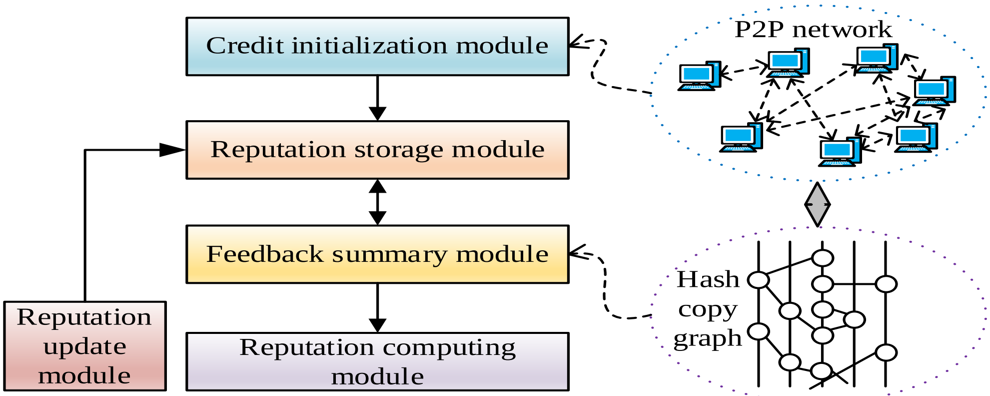


Figure 2. Flowchart of the improved Hashgraph

In Figure 2, the node behavior is assigned an initial reputation value through the initialization module, and the interaction records are collected in the feedback aggregation module. The node reputation is dynamically adjusted through the update module. This mechanism aims to suppress the behavior of malicious nodes, thereby enhancing the system’s stability and credibility during information synchronization. Nodes will only actively contribute and assist the system when they expect to receive clear benefits. This results in a polarized attitude among nodes: active nodes collaborate with the system to gain mutual benefits, while passive nodes may resort to illegal means, such as attacking active nodes or spreading false information, in order to gain without contributing [18]. Therefore, when new nodes join, different reputation values are assigned based on the actual conditions of each node through an initialization module. The scoring of the initial honor value is shown in Equation (2).

$$IN(n)=\sum_{j=1}^{k}\lambda_j * W_j \qquad (2)$$

In Equation (2), n represents the node, λ represents the node score, W represents the node weight, and j represents the side factors. During the continuous information transmission and interaction process of the nodes, the feedback aggregation module collects the hash replica graph and gathers the feedback information. Meanwhile, the storage module records the reputation scores of each node. In the following interaction stage, the update module dynamically updates the reputation values of the nodes, and the calculation module then obtains the final reputation value at each time point. As can be seen, by combining Hashgraph with the reputation model, effective mobilization and monitoring of node characteristics can be achieved. Therefore, the BIM system architecture based on reputation and Hashgraph is shown in Figure 3.

The architecture in Figure 3 is divided into three layers. The bottom layer is the node reputation evaluation module, which quantifies node behavior from four dimensions: computing power, security, initiative, and loyalty. The middle layer is the Hashgraph consensus network, which is responsible for event synchronization and consensus formation among nodes. The top layer is the BIM application layer, which supports collaborative design and operation and maintenance management. The selection of these four dimensions is based on the actual needs of BIM collaborative work. The computing power ensures that nodes can handle complex BIM model rendering and simulation calculations, avoiding overall collaborative progress from being slowed by hardware bottlenecks. Security is directly related to the safety of project data assets. A vulnerable node may leak the critical information of the entire project. Enthusiasm indicates whether the participant remains online and continues to provide services. Frequent offline activities can disrupt the continuity of the consensus process. Loyalty reflects whether the participants adhere to the project plan, submit design results in a timely manner, and respond to requests, which is crucial for ensuring the project schedule. By assigning reputation values to each node through precise quantification, a reliable basis for system management is provided. The calculation process of the base reputation value is shown in Equation (3).

$$D(u_i)=\alpha Sc+\beta Pa+\gamma Fd+\delta Rt \qquad (3)$$

In Equation (3), Sc represents the remaining computing power of the node, Pa represents the probability of the node being attacked, Fd represents the offline frequency of the node, and Rt represents the node’s information transmission time. α, β, γ, and δ represent the weights of different projects, with their sum equal to 1. The error rate of the node is determined by the feedback on the transmission results from the nodes it communicates with. The study defines the error rate as a negative indicator, and accordingly, nodes that transmit information correctly are incentivized with positive points to optimize the system’s feedback mechanism. Therefore, the final reputation value of the node is shown in Equation (4).

$$C(u_i)=D(u_i)+\theta num(u_i)-Mis(u_i)\Delta\sigma \qquad (4)$$

In Equation (4), $num(u_i)$ represents the number of correct information transmissions by node i, $Mis(u_i)$ represents the number of incorrect transmissions by node i, $\Delta\sigma$ represents the penalty points for transmission errors, and $\theta \square \Delta\sigma$. This ensures that the reputation value comprehensively reflects the reliability, security and willingness to collaborate of the node in collaborative design. The reputation mechanism ensures that nodes with higher reputation values can obtain greater benefits when assisting in the operation of the system. This reverse incentive motivates nodes to regulate their own behavior, earning more rewards through active work. In the consensus phase, a leader is selected to determine the plan. The specific process is as follows: during information transmission, the consensus round is first clarified, and the leader for this round is determined based on the node’s reputation value. Then, the leader leads the nodes to make decisions on events, reaching a consensus.

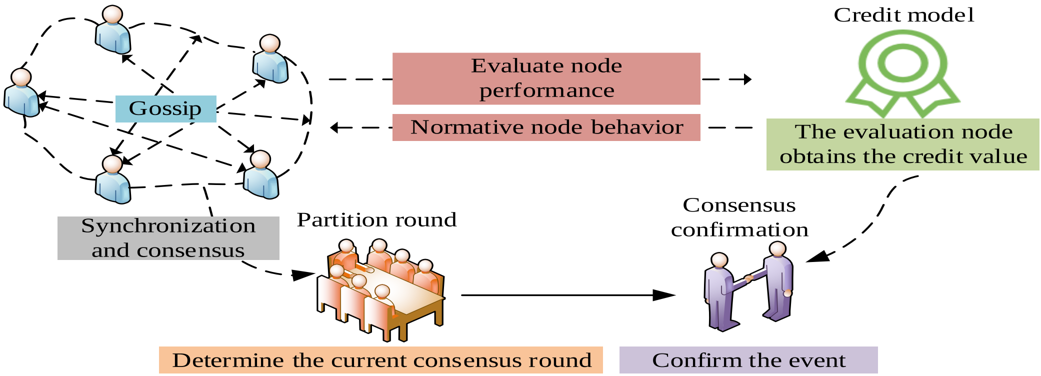


Figure 3. The BIM system architecture based on reputation and Hashgraph

3.2. Construction of a collaborative design model based on Hashgraph-BIM

Based on the constructed BIM, the study further integrates the leader selection algorithm into the technology for optimization. The introduction of the leader mechanism in the algorithm inevitably raises security concerns. For instance, Byzantine nodes may refuse access to the leader node, interfering with its information synchronization process, thereby reducing information transmission efficiency. If the leader node itself is a Byzantine node, it may intentionally reduce the information transmission frequency [19]. To address these issues, the study selects non-repeating leaders for different consensus rounds, ensuring that nodes cannot obtain leader information in advance and launch attacks. Additionally, the leader selection algorithm adjusts the likelihood of each node being chosen as the leader based on its reputation value. This ensures the efficiency and security of the leader when processing information. The structure of the leader selection algorithm is shown in Figure 4 [20].

Figure 4 shows that the trigger starts from the new round of consensus. Nodes generate temporary key pairs through a random lottery mechanism, and the lottery results are stored in the "witness unit" and publicly verified. Through this structure, the algorithm achieves the unpredictability of the leader and the public verifiability of the selection process, preventing nodes from predicting the leader and launching attacks while ensuring the authenticity and immutability of the lottery results. The draw process is as shown in Equation (5).

$$keygen(r) = (Vk, SK) \tag{5}$$

In Equation (5), Vk represents the temporary public key, and SK represents the temporary private key. The drawing result is then calculated, as shown in Equation (6).

$$value = VRF\_hash(SK, R) \tag{6}$$

In Equation (6), VRF represents the randomly verifiable function. Equations (5) and (6) can ensure that the election process is unpredictable and publicly verifiable, preventing malicious nodes from learning the leader's identity in advance and launching attacks. When other nodes acquire the lottery information stored in the witness unit, they will verify the authenticity of the information. Nodes that pass the verification will be selected as the leader for the current round. This algorithm ensures the reliability of the lottery information while the nodes do not yet know the private keys of other nodes. It ensures the confidentiality of the leader selection process, preventing nodes from discovering the leader in advance and launching attacks, thereby safeguarding the security of the leader. Therefore, the Hashgraph combined with the leader selection algorithm is shown in Figure 5.

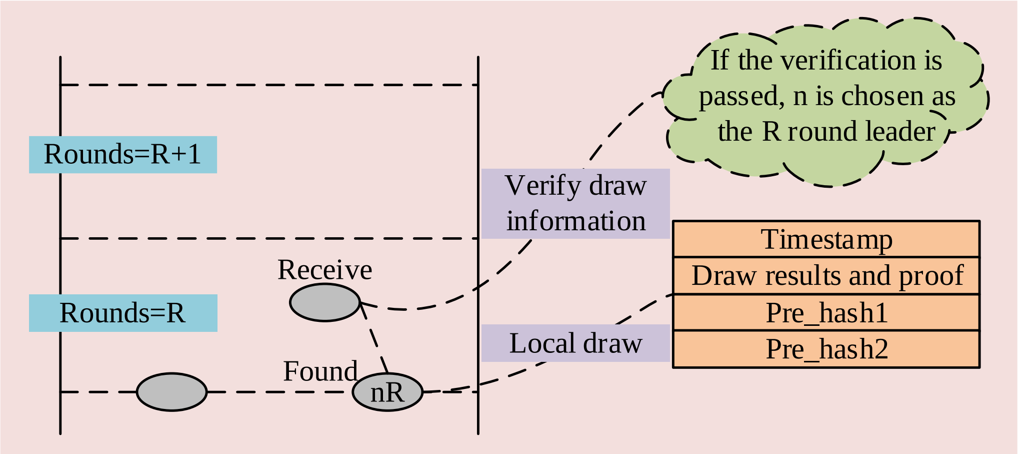


Figure 4. Leader selection algorithm structure diagram

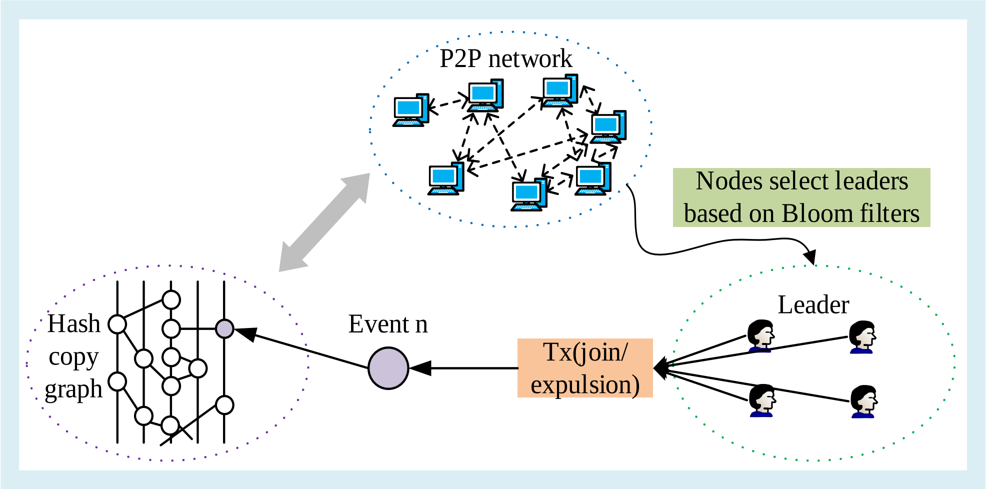


Figure 5. Hashgraph processes combined with leader selection algorithms

In Figure 5, the key steps of new node joining, leader election, reputation assessment, and node eviction are connected by arrows to demonstrate their temporal relationships and logical dependencies. It reflects the security and efficiency of the dynamic leadership mechanism and the collaborative design of the reputation supervision improvement system. The specific process is as follows. First, the process of adding new nodes is shown in Equation (7).

$$Tx(join)=\langle r_1, pk, t_1, \partial_1(r_1 \parallel pk \parallel t_1)\rangle \tag{7}$$

In Equation (7), r_1 represents the random number, ∂_1 represents the joining node's signature, t_1 represents the joining time, and pk represents the joining node's public key. When nodes join the network, they will randomly determine their respective leader nodes, and this determination is accomplished using a Bloom filter. The expected number of leaders for each node is shown in Equation (8).

$$\bar{J}=\sum_{i=1}^{N}(1-p)^{k} \tag{8}$$

In Equation (8), N represents the total number of nodes, p represents the probability of node i based on the filter, and k represents the number of hash functions in the Bloom filter. When a new node joins, the leader node verifies the transaction information, signs it, and announces the new node's details to all other nodes, as shown in Equation (9)."

$$\begin{aligned}Tx(newnode)=\langle & r_1, pk, t_1, \partial_1(r_1 \parallel pk \parallel t_1), r_2, pk_2, t_2,\\ & \partial_2(r_1 \parallel pk \parallel t_1 \parallel \partial_1 \parallel r_2 \parallel pk_2 \parallel t_2)\rangle\end{aligned} \tag{9}$$

In Equation (9), pk_2 represents the public key of the leader node, t_2 represents the joining time proof, and ∂_2 represents the signature of the leader node. During the node's assistance work, the leader will periodically check its reputation score. Once a node's reputation score falls outside the acceptable range of the system, it will be subject to continuous observation. If, within the specified time, the node's reputation score still does not meet the required standard, the leader will initiate a vote to decide whether to expel the node from the transaction network. The specific process is shown in Equation (10).

$$Tx(vote)=\langle r_3, pk_3, t_3, \partial_3(r_3 \parallel pk_3 \parallel t_3)\rangle \tag{10}$$

In Equation (10), pk_3 represents the public key of the leader node, t_3 represents the voting time, and ∂_3 represents the leader's signature. When more than half of the leader nodes reach a consensus that a node's reputation score has deviated from the system's established standards, the relevant leader nodes will sign and publish an expulsion transaction. The expulsion process is shown in Equation (11).

$$\begin{aligned}Tx(\exp ulsion)=\langle & r_4, pk_i, pk_j, t_3, t_4,\\ & \partial_j(r_4 \parallel pk_i \parallel pk_j \parallel t_3 \parallel t_4)\rangle\end{aligned} \tag{11}$$

In Equation (11), i represents the expelled node, j represents the leader, and t_4 represents the expulsion time. After the expulsion transaction is completed in the network, all nodes will delete all information related to the expelled node. Therefore, to ensure the efficiency of information synchronization consensus, the study proposes a collaborative design model of Hashgraph-BIM combining reputation, and the leader selection algorithm. The basic process is shown in Figure 6.

As shown in Figure 6, the steps of the collaborative design model are as follows: First, an initial plan is designed, and design parameters are selected based on the object to be designed. Then, all participating parties collaborate to optimize these parameters. A 3D information model is created based on these parameters, and design schemes are evaluated based on factors such as cost and building energy consumption. The cost calculation formula is shown in Equation (12).

$$\begin{cases}DC=MC+LC+MC\\ IC=MF+FF+EF\end{cases} \tag{12}$$

In Equation (12), DC represents direct costs, while MC, LC, and MC refer to material, labor, and machinery costs, respectively. IC denotes indirect costs, and MF, FF, and EF represent management, financial, and energy expenses. After comparing the indicators of each scheme, if the design meets the expected range, the design is finalized and outputs, followed by actual manual testing before the implementation phase. If the target optimization range is not met, further parameter optimization is performed through optimization methods, and the collaborative design process is resumed.

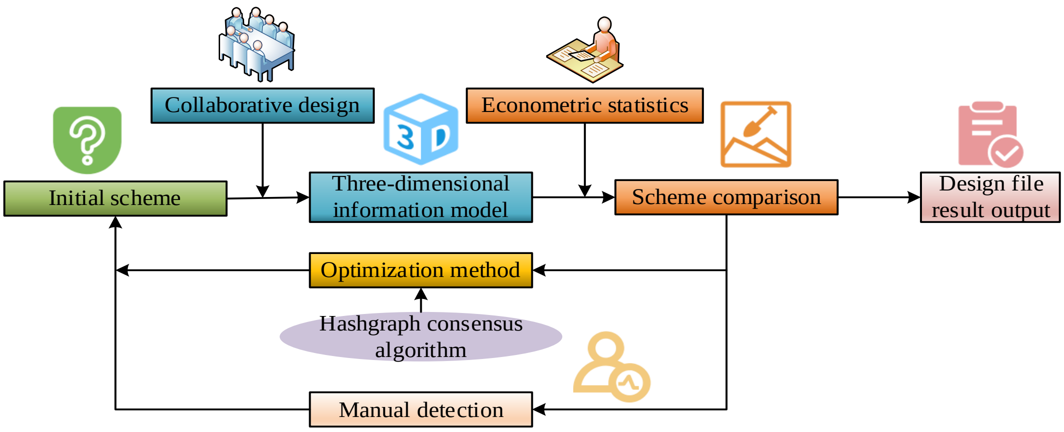


Figure 6. Hashgraph-BIM collaborative design modeling flowchart

4. VERIFICATION OF HASHGRAPH-BIM AND ITS COLLABORATIVE DESIGN MODEL

4.1. Performance verification of improved Hashgraph in BIM

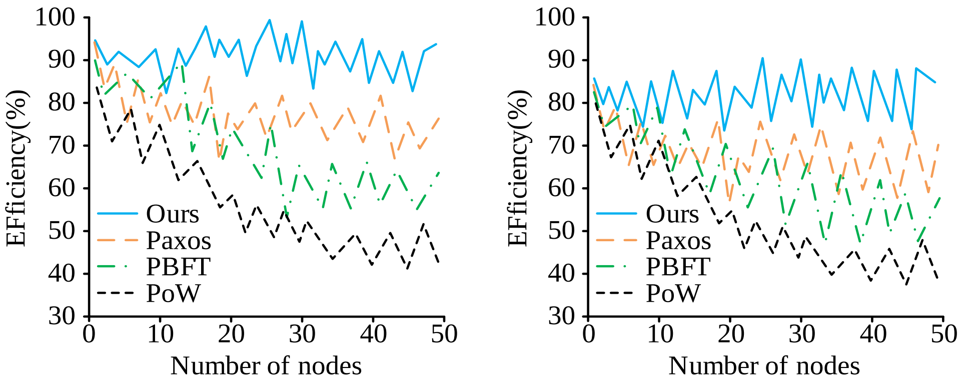
To verify the performance of the Hashgraph-BIM model combined with the credibility and leader selection algorithms, and its ability to meet the requirements of collaborative design, the study compared it with commonly used consensus algorithms such as Paxos, Proof of Work (PoW), and Practical Byzantine Fault Tolerance (PBFT). Among them, the Paxos algorithm, a classic message-passing consensus algorithm, is primarily used to ensure that distributed systems reach consistency despite non-Byzantine faults (such as node crashes and network delays). It is widely applied in many distributed databases and coordination services. The PBFT algorithm can tolerate up to one-third of Byzantine nodes and uses a three-stage protocol to reach consensus. As the core algorithm of public blockchains such as Bitcoin, the PoW algorithm competes for the right to record transactions by requiring nodes to perform time-consuming mathematical calculations. Node deployment: The research used Docker to create a separate container instance for each consensus node. These containers share the hardware resources of the host, but are isolated from each other on the network stack, process space, and file system, thereby precisely simulating the behavior of multiple independent hosts in a distributed system. To simulate latency in a real network, the research employed a tool that affected the virtual network interface of the D container, allowing us to inject controllable latency into communication between each node pair. For instance, in the “high network latency” test scenario, we set a random delay of 50-200ms for all container communications to simulate a wide-area network environment. Passive node modeling: Passive (or Byzantine) nodes are implemented by running customized fault injection scripts in the corresponding Docker containers. These scripts will interfere with nodes’ normal behavior according to preset strategies (such as random packet loss, random delays in response, or complete nonresponse to consensus messages), thereby simulating uncooperative or malicious participants in the project. To ensure the fairness and scientific nature of the experiment, all different methods were tested under the same conditions, and the number of repeated runs was set at five times. The experimental environment and equipment setup are shown in Table 1.

Based on the above experimental environment, a simulation experiment on consensus and virtual voting was conducted for the four algorithms. The performance of the algorithms was measured by evaluating consensus efficiency, throughput, and memory usage. Among them, the consensus accuracy rate is the success rate with which all honest nodes reach a final consensus on the sequence and content of BIM events in the simulated distributed BIM collaborative environment. The test of this indicator assumes that the number of malicious nodes does not exceed the system’s theoretical fault-tolerance upper limit (1/3 of the total number of nodes in the proposed model). Throughput refers to the amount of valid data that a system successfully processes and reaches consensus on within a unit of time. It is necessary to calculate the total number of bytes of the payload contained in the Hashgraph events finally confirmed locally by all nodes within a fixed time window, and then compute the average time. Memory usage refers to the amount of computer memory consumed by a single node during the consensus process to maintain the Hashgraph data structure, node status, and the reputation model. It is directly related to the model’s scalability. The slower the memory usage grows with the number of nodes, the more capable the algorithm is of supporting the collaboration of large-scale projects. The experiment set up two information broadcasting intervals of 300ms and 600ms to simulate the collaborative working rhythm of high-intensity and conventional-intensity. The basis for the above numerical Settings mainly comes from two aspects. On the one hand, it refers to the common operation response and data synchronization delay range in the building collaborative design system to simulate the interaction frequency between design nodes in the actual engineering environment. On the other hand, it follows the commonly used benchmark interval for performance testing distributed consensus algorithms. In addition, by setting differentiated interval values, the stability and scalability of the algorithm in high-frequency and low-frequency transmission scenarios can be analyzed more comprehensively. The comparison of consensus efficiency across different information transmission intervals, numbers of passive nodes, and network delays is shown in Figure 7.

Table 1. The experimental environment and equipment

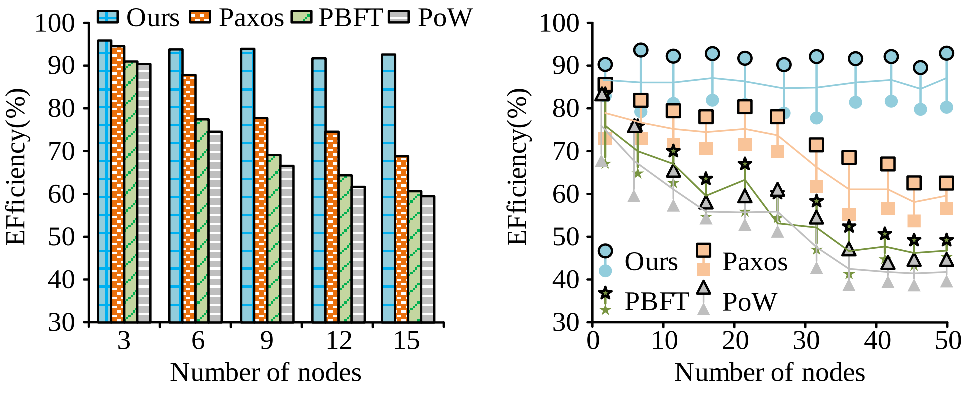
Item	Disposition
Operating system	Microsoft Windows 10
CPU processor	Intel(R)Core(TM)i5-7300HQ CPU @2.50GHz
GPU	NVIDIA RTX 3070s
Internal memory	32G
Video memory	16G
Hard disk	Colorful SL500 1TB
Java version	JDK11.01
Browser version	Google Chrome version 80.0.3987.149 (Official version) (64-bit)

Figure 7(a) shows the comparison of consensus efficiency when information was transmitted every 300 ms, and Figure 7(b) shows the comparison of consensus efficiency when information was transmitted every 600 ms. As shown in Figures 7(a) and 7(b), under different information transmission frequencies, the consensus efficiency of Hashgraph-BIM outperformed the comparison algorithms, reaching a maximum of 95.3% and 91.2%, respectively. Moreover, the efficiency of Hashgraph-BIM showed little change as the number of consensus nodes increased, while the efficiency of the other three algorithms decreased to some extent. Figure 7(c) shows the impact of the number of passive nodes on each algorithm. It can be seen that Hashgraph-BIM was less affected by the number of passive nodes, maintaining an average accuracy of 92%. Figure 7(d) shows the comparison of each algorithm under different network delay conditions, where Hashgraph-BIM was less impacted by network delay, maintaining a consensus efficiency of 84% even under high delays, significantly outperforming the comparison algorithms. Overall, Hashgraph-BIM maintained good consensus efficiency across various environments. To further validate the applicability of Hashgraph-BIM, experiments were conducted to compare the memory usage of each algorithm in an environment with a 300 ms transmission frequency and low network delay. The results are shown in Figure 8.



(a) The information transmission interval is 300ms

(b) The information transmission interval is 600ms



(c) Number of passive nodes

(d) High and low network delays

Figure 7. Comparison of consensus efficiency of different algorithms in different cases

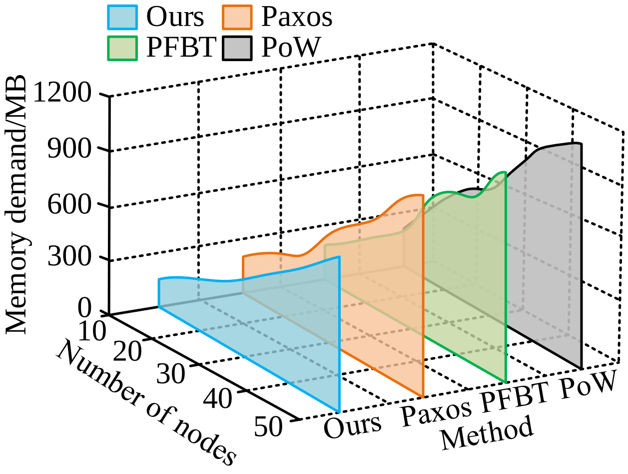


Figure 8. Comparison of the memory usage of each algorithm

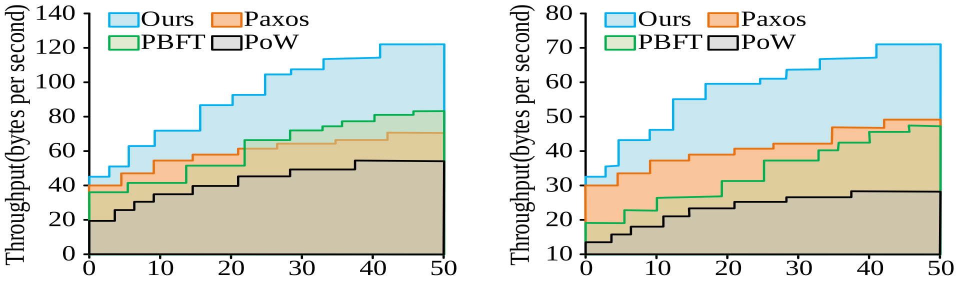
As shown in Figure 8, when the number of consensus nodes increased, Hashgraph-BIM's memory usage increased slowly, eventually stabilizing around 582 MB, and its memory usage throughout the consensus process was consistently lower than that of the comparison algorithms. On the other hand, the comparison PoW algorithm experienced a rapid increase in memory usage once the number of consensus nodes reached a certain threshold. It can be seen that with the increase in the number of consensus nodes, Hashgraph-BIM's advantage in memory usage became more evident. Overall, Hashgraph-BIM exhibited less performance fluctuation when facing an increase in consensus nodes, demonstrating more stable and efficient data processing capabilities compared to the other algorithms. To further validate Hashgraph-BIM's ability to handle information, throughput comparisons were conducted under different information transmission intervals, the number of passive nodes, and network delays. The results are shown in Figure 9.

As shown in Figure 9(a) and Figure 9(b), under different information transmission frequencies, Hashgraph-BIM's consensus throughput was significantly superior to that of the comparison algorithms, reaching a maximum of 120 bytes per second and 70 bytes per second, respectively. Figure 9(c) shows the impact of the number of passive nodes on the throughput of each algorithm. With the increase in the number of passive nodes, the throughput of all algorithms decreased to some extent, but Hashgraph-BIM's throughput remained superior throughout the process compared to the other algorithms. As shown in Figure 9(d), when comparing the effects of different network delays on each algorithm, Hashgraph-BIM maintained a throughput of 20 bytes per second under high network delay and 35 bytes per second under low delay, significantly outperforming the comparison algorithms. Overall, Hashgraph-BIM was able to maintain strong information processing capabilities across various environments.

4.2. Performance verification of operation and maintenance management of collaborative design model based on Hashgraph-BIM

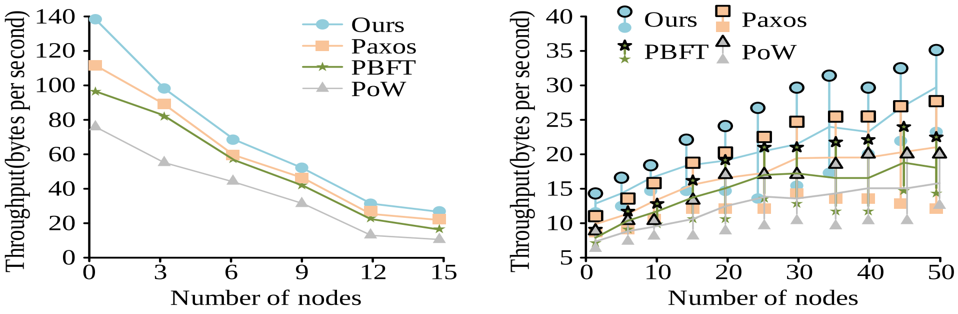
After validating the improved Hashgraph performance, in order to further verify whether the Hashgraph-BIM-based collaborative design model could meet the needs of collaborative design and later building operation and maintenance, the study established a collaborative design, and operation management model using a certain energy plant as the experimental object. The developed model was compared with collaborative design models based on Paxos, PFBT, and PoW in terms of design optimization performance. The results comparing the costs of building rebar, concrete, panels, and labor in the design plans are shown in Figure 10.

As shown in Figure 10, the highest proportion of the total project cost was for the panel cost at 34.74%, while the lowest proportion was for labor costs at 17.29%. The design scheme proposed by Hashgraph-BIM had lower costs in all aspects compared to the reference models. Its total cost was only 1.8423 million yuan, which represented a 12.14% optimization compared to the highest cost of 2.0968 million yuan. Overall, the collaborative design scheme proposed by Hashgraph-BIM proved to be more economically efficient, with its design optimization performance significantly surpassing that of the reference models. Following this, the building operation and maintenance effect of Hashgraph-BIM was tested, and the estimated cost savings per year for building operation and maintenance are shown in Figure 11.



(a) The information transmission interval is 300ms

(b) The information transmission interval is 600ms



(c) Number of passive nodes

(d) High and low network delays

Figure 9. Comparison of throughput of different algorithms under different conditions

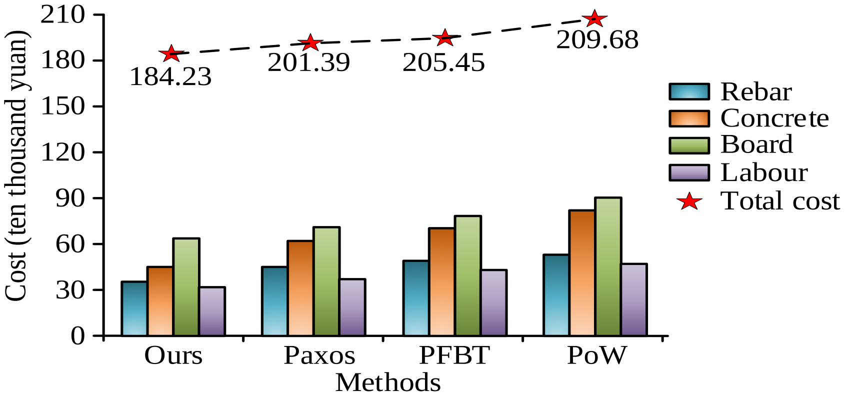
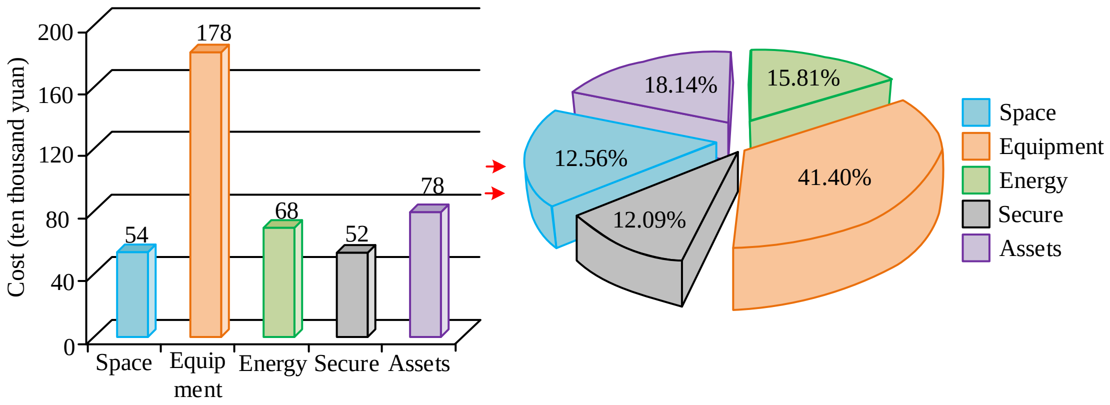


Figure 10. Cost comparison results of design options



(a) Cost-saving aspect

(b) Proportion of cases in each cluster

Figure 11. Cost savings test results

As shown in Figure 11, during the building operation and maintenance phase, Hashgraph-BIM created significant economic benefits in five key modules: safety management, space management, energy consumption management, asset management, and equipment management. The reduction in costs for each module was considerable, with savings of 520,000 yuan, 540,000 yuan, 680,000 yuan, 780,000 yuan, and 1.78 million yuan, respectively. The proportions of total cost reduction for these modules were 12.09%, 12.56%, 15.81%, 18.14%, and 41.40%, resulting in a total annual savings of 4.3 million yuan. This achievement stems from the high-precision, conflict-free BIM model generated during the design phase, providing a reliable digital twin foundation for subsequent operations and maintenance. These savings are not achieved by reducing service quality, but by improvements in management efficiency brought about by models: for instance, energy simulation based on precise models optimizes energy consumption, preventive maintenance prevents sudden failures of expensive equipment, and integrated asset information significantly enhances management efficiency. This fully demonstrates that the in-depth collaboration and high-quality design in the early stage are the fundamental guarantee for achieving efficient and low-cost management in the operation and maintenance phase. In addition, this model is applicable not only to construction engineering but also to scenarios in industrial systems engineering, such as flexible production line scheduling, distributed supply chain collaboration, and status synchronization in intelligent manufacturing systems. The performance metrics used in the model, such as throughput, memory utilization rate and cost optimization rate, are consistent with the commonly used system efficiency, resource utilization rate and process economy evaluation metrics in industrial engineering, reflecting the cross-disciplinary universality and portability of the model.

5. DISCUSSION

The BIM collaborative model, based on Hashgraph and a reputation mechanism developed by the research, has demonstrated significant advantages across all key indicators. Since Paxos is a classic distributed consensus algorithm, it represents efficient consensus in non-Byzantine environments. PoW is the most widely used but resource-consuming consensus mechanism in blockchain. PBFT is a commonly used Byzantine fault-tolerant algorithm in consortium chains. The three, respectively, represent consensus design paradigms under different trust assumptions and resource constraints, which form a sharp contrast with Hashgraph in terms of fault-tolerant models, communication complexity, and energy efficiency, and can comprehensively evaluate the performance of this model. Therefore, the study chose the above-mentioned methods for comparison. The experimental results show that this model can effectively address common challenges in real collaborative environments, such as node dynamics, network latency, and negative nodes. The fundamental reason is that the model deeply integrates the asynchronous Byzantine fault tolerance feature of Hashgraph with the dynamic reputation management mechanism, achieving a unified improvement in efficiency and credibility. This not only provides a new technical path for full life-cycle collaboration in construction projects, but also offers transferable references for scenarios such as distributed production systems and supply chain collaboration in industrial engineering. The robustness against negative nodes and network latency comes from Hashgraph’s adoption of the “gossip-about-gossip” protocol for event propagation. Nodes achieve information diffusion through multiple rounds of random communication. Its gossip-about-gossip mechanism can still maintain the final consistency of information when there is network latency or some nodes are negative. By integrating the reputation model, the system can identify and reduce the weight of low-reputation nodes in the consensus, thereby weakening their negative impact.

Because Hashgraph uses a directed acyclic graph to record event history, it does not need to maintain a continuously growing chain like PoW, nor does it need to store multi-stage message copies like PBFT. Therefore, the memory usage grows more gently with the number of nodes, and the system has better scalability. Meanwhile, Hashgraph has no mining competition or multi-round voting overhead. Its asynchronous consensus mechanism and event parallel processing capability make it stand out in high-frequency information synchronization scenarios, especially suitable for frequent design changes and status updates in BIM collaboration.

The experimental hardware configuration (RTX 3070, 32GB RAM) simulated the typical performance level of collaborative workstations in medium to large design enterprises, and was capable of supporting collaborative editing and real-time synchronization of BIM models involving multiple professional teams, such as architecture, structure, mechanical and electrical, and component numbers at the 10^4-10^5 level. The scale of the experimental nodes this time corresponds to a medium-sized project collaboration scenario with 5 to 15 participants. In addition, both the cost and savings data were calculated based on 10 independent and repeated experiments. The coefficient of variation (CV) of the cost results for each scheme is all below 5%, indicating high stability and reproducibility.

In conclusion, the proposed model promotes the transformation of the construction industry model by building a decentralized, real-time trustworthy, and resource-efficient collaborative infrastructure. It not only resolves the issues of information silos and lack of trust in traditional BIM collaboration, but also lays the foundation for advanced applications such as the automatic execution of smart contracts, real-time synchronization of digital twins, and cross-organizational process collaboration.

6. CONCLUSION

This study proposes a collaborative design, operation, and maintenance management model based on Hashgraph and BIM to address the core issues of lagging information synchronization and a lack of collaborative trust in traditional construction projects. Experiments show that this model significantly outperforms existing consensus algorithms, achieving a consensus efficiency of up to 95.3% and a throughput of 120 bytes per second. It has achieved 12.14% cost optimization and annual operational and maintenance savings of 4.3 million yuan in actual energy plant projects. This model realizes decentralized, real-time and reliable full-process information synchronization, supporting seamless connection among the design, construction and operation and maintenance stages. Through dynamic reputation mechanisms and verifiable leader elections, a collaborative trust foundation without a central authority has been established, laying the technical foundation for automated compliance verification and milestone payments. However, the research still has limitations: the experiments were only conducted on energy plant buildings and did not verify their scalability when dealing with tens of thousands of nodes and components in large and complex projects (such as airports). The evaluation indicators mostly focus on cost and efficiency, lacking a comprehensive assessment of design quality, construction period, user satisfaction and other performance aspects. Future research can verify the model's universality across various project types, such as residential and public buildings, and conduct ultra-large-scale node stress tests. Introduce identity binding and behavior analysis mechanisms to enhance system security; Promote the implementation of technologies, including integrating smart contracts to achieve automatic payment and fusing IoT data to update operation and maintenance status in real time, and carry out pilot applications in real multi-party construction projects.

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