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Integrated digital twin and blockchain framework to support accountable information sharing in construction projects

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ABSTRACT

Efficient collaboration among various stakeholders is important for the successful completion of a construction project. However, stakeholders in construction are fragmented, which in turn hinders accountable information sharing. To address this issue, the authors aim to develop and test an integrated digital twin and blockchain framework for traceable data communication. The digital twin updates building information modeling in near real-time using internet of things sensors, while the blockchain authenticates and adds confidence to all data transactions to the digital twin. The authors tested the framework with a case project where virtual positioning data from a prefabricated brick is transmitted to digital twin in near real-time, recorded on the blockchain with time stamps. The results show that the integrated digital twin and blockchain framework makes all data transactions traceable. This paper's primary contribution is the development of a framework that realizes accountable project-related information sharing across stakeholders.

1. Introduction

Efficient collaboration among project participants is a key factor in completing construction projects on time and within budget. The precedent of collaboration is to share accountable information among the participants [1]. However, the construction industry is fragmented, with many geographically dispersed participants working together toward a common goal [2]. This fragmentation spurs inconsistency and delays in data communication among the participants and deprives accountability for project-related information sharing.

Several studies have noted that digital twin technology has immense potential to support information sharing among project participants [3,4]. The digital twin is a virtual representation of physical assets [5], which corresponds to sensory data used to visually represent real-time information. Project participants can share up-to-date project-related information with frequently updated representation. However, to allow accountable information sharing among fragmented participants in the digital twin, all data transactions should be transparent without any potential manipulation. In other words, any data in the digital twin should be tamper-proof and shared traceably among the participants. However, the data management of a digital twin, including data storage, security, and sharing, has not yet been thoroughly realized.

To address this issue, the authors aim to develop and test an integrated digital twin and blockchain framework which can selectively store and share important project-related information traceably. Blockchain is a peer-to-peer network ledger technology [6] that authenticates and adds traceability to any data transaction and is integrated with the digital twin in this research. Blockchain also creates a decentralized consensus mechanism among project participants to authenticate and consent on the integrity and accuracy of the transaction [7]. As a result, any information can be shared securely and transparently [8], which makes all information sharing in the digital twin accountable. With such information, current lengthy contract and payment executions can be automated and quickly advanced through a smart contract, which is a self-executing contract protocol intended to automatically facilitate, verify, or enforce an agreement according to the terms of a contract. Consequently, it will facilitate more effective collaboration among fragmented participants, improved project efficiency and customer satisfaction.

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2. Digital twin in construction

A digital twin is a virtual replica of physical assets, process, system or service which represents the properties (e.g., the geometry of assets), the condition (e.g., resource status), and the project's performance [9–11]. The digital twin was first proposed in the product lifecycle management field [12] and studied in the aircraft and aerospace fields as a mirroring model for simulating an as-built vehicle, system, or process [13,14]. Since then, it has been applied in manufacturing [15], transportation management [16], city-level governance [17], the pharmaceutical industry [18], health care and the medical system [19], and legal contracts [20]. The core technology of the digital twin is data synchronization between the physical asset and its virtual representation [15]. Recent advancements in internet of things (IoT) technology allows the digital twin to be synchronized with physical counterparts even in real-time. Such synchronization allows effective monitoring and data analytics (e.g., simulation) for the physical counterparts throughout their lifecycle to enable proactive maintenance, develop new opportunities, and plan for future operations.

In a construction project, building information modeling (BIM) is a digital representation of what will be built [21]. The digital twin goes beyond the BIM for more "up-to-current" modeling. With the aid of empowered IoT sensors, the digital twin can make BIM a living instrument, automatically updating 'as-built' BIM. In addition, the digital twin can be used to simulate "what-if" scenarios using artificial intelligent-based techniques to find out potential solutions against arisen issues such as cost overruns and schedule delays, which enables practitioners to proactively take a control action. Previously, Lu et al. [22] integrated the digital twin with industry foundation classes (IFC) and daily operation and management data for anomaly detection and operation and maintenance (O&M) management in an HVAC system. Pan et al. [23] integrated BIM, IoT, and data mining techniques to simulate both task execution and worker cooperation. They then predicted the future construction process to optimize construction operations by arranging work and staffing according to the changeable site conditions. Boje et al. [24] emphasized the importance of an intelligent digital twin which includes holistic, scalable semantics as well as the importance of knowledge about the physical world for a smart and lean construction. Shim et al. [25] integrated BIM and digital inspection systems using image processing for preventive bridge maintenance. These studies show that the digital twin holds potential to monitor performance, detect issues, assess what-if scenarios in the virtual space and obtain valuable insights for proactive management and effective collaboration with the customers in a construction project—whether built or in progress.

One of the important potential benefits of having a digital twin in a construction project is to support data communication among project participants [4]. Kaewunruen et al. [26] applied the digital twin for a subway station project and Pan et al. [23] applied it for a house construction project in order to facilitate better team communication among stakeholders. Sepasgozar [27] combined the digital twin with augmented reality for immersive data communication and education and Shirowzhan et al. [28] suggested smart city information sharing framework based on geographic information system. They have noted that project participants can share information on current and future tasks with "up-to-current" representations and "what-if" scenarios with the digital twin. These studies show that the digital twin can be a powerful data communication tool in construction, but they have not fully discussed how such communication ultimately leads to effective team collaboration.

In order for the digital twin to support true collaboration beyond just communication tools, all representations of the digital twin must be reliable. If such a representation is reliable enough to check participants' performance, it can also be used for compliance checking against a contract. Compliance checking involves determining if the participants have maintained records consistent with the pre-agreed contract; it guarantees that work within a project goes forward as planned and according to requirements and standards. In the digital twin, the "up-to-current" (as-built) BIM can be compared to as-planned BIM automatically for compliance checking, allowing the contractor to make appropriate and faster decisions on contract executions and payment which can reduce disputes and conflicts between participants—ultimately leading to effective team collaboration.

However, because virtual representations in a digital twin are often updated to show the real-time state of physical assets, data from a digital twin is vulnerable to overwriting [29]. The historical data of virtual assets could be lost after a digital twin is overwritten. Historical data of virtual assets can record the sub-contractors' performance, progress details of the project, and the project's compliance status—all of which are important project-related data necessary for trustful collaboration. Therefore, when using a digital twin for accountable information sharing, any overwritten actions should be recorded securely and historically. In other words, all the data in a digital twin should be stored in a tamper-proof manner and shared traceably. However, the data management of a digital twin, including data storage and sharing, which should be immutable and traceable has not been thoroughly realized [29].

3. Potential of blockchain technology for digital twin in construction

Recently, several researchers have noted that the potential value of blockchain technology within the data management of digital assets in terms of data storage, security, and sharing [29–32]. Blockchain technology is a decentralized peer-to-peer distributed network ledger that consists of a sequence of chronological blocks [33,34]. Each block contains a cryptographic hash of the previous block, a timestamp, and transaction data. Thus, the data stored in the block cannot be altered retroactively, without the alteration of all subsequent blocks. Also, in the peer-to-peer network, members maintain their copies of the data, and all members authenticate any updates. Thus, any data can be shared immutably and traceably without an intermediary (e.g., bank) [35].

Blockchain was initially designed as a system for running the digital cryptocurrency, Bitcoin. However, it has also been applied in many different areas such as supply chain management [36], privacy preservation [34,37,38], electronic voting [39], and big data management [30]. In the construction industry, blockchain has been applied to IoT data security on construction sites for more reliable data transactions [40], information management during building life-cycle stages [41], automated payments [42], and intelligent contracting [43]. More specifically, many studies have focused on the potential benefits of blockchain for BIM data sharing. For example, Zheng et al. [31] suggested a mobile cloud-based blockchain model for BIM modification audit and provenance. They argued that their model may guarantee BIM data integrity and facilitate ubiquitous accessing of BIM information. Nawari et al. [44] suggested an automated code compliance checking method based on BIM and blockchain for the application of the smart contract. Xue et al. [45] suggested a semantic differential transaction approach to minimize information redundancy in a BIM project. Their model captures the version history of a BIM project with timestamps to synchronize BIM changes among project participants. These studies show that blockchain can make BIM data traceable, immutable, and deliverable without an intermediary thus accelerating BIM workflow during construction. Therefore, it might be a valuable benefit for a digital twin in construction to require BIM as a key data input.

However, due to its inefficiency in storing large data, blockchain is inherently not designed for data storage [30]. For example, Bitcoin can store 1-megabyte size data in a block and it takes 10 min to update and share a new block. As such, it is difficult to store and share all sensor data and as-built BIM files from a digital twin in blockchain. Therefore, when applying blockchain to the data management of a digital twin, only the important updates essential for collaboration should selectively be stored and shared. Moreover, it has not yet been proven that all data in a digital twin that evolves in near real-time can be traceably shared on such blockchain with limited storage.

4. Integrated digital twin and blockchain framework for traceable data communication

To secure the data traceability of a digital twin while overcoming the limited storage of blockchain, the authors aim to develop an integrated digital twin and blockchain framework that can selectively store and share important project-related information traceably. Blockchain records all data transactions occurring in the digital twin traceably, making them transparent enough for reliable transactions. With such reliable transactions, the digital twin can perform a compliance check to generate a 'compliance statement' that can be traceably shared on the blockchain network. The compliance statement verifies whether all project participants' progress complies with predefined agreements or rules. The participants can share only this compliance statement, which enables important project-related information to be shared traceably on the blockchain network without the need to store all the data. This makes our framework efficient and accountable, thereby facilitating collaboration.

4.1. Framework overview

The integrated digital twin and blockchain framework consists of six components as shown in Fig.1. This framework shows how project data is collected on the construction site and updates the as-built BIM in the digital twin. Also, it explains how the as-built BIM, which evolves over time, can be transformed into the compliance statement and how such a statement can be stored and traceably shared among project participants on the blockchain network with limited storage. The core idea of this framework is that the blockchain network does not store all the data from sensors or digital twin, but only stores and shares a 'compliance statement' that is essential for collaboration.

Specifically, the IoT sensors attached to physical assets collect real-time sensor data from a construction site (Fig.1-(a)) and transmit the data to a virtual space in the digital twin (Fig.1-(b)). Digital twin updates the as-built model by combining the sensor data and as-designed BIM in the virtual space, and checks the compliance with the as-planned BIM. Such compliance checking ensures whether all project participants' progress complies with predefined agreements and rules. The result of the checking is documented as a compliance statement which is a legally effective document confirming all project participants' records (Fig.1-(c)). The records serve as important information for collaboration because the contractor can make an appropriate and fast decision related to contract executions and payment based on the records. More importantly, the compliance statement does not require large data storage because it stores only the participants' records as statements (e.g., proposition and logic) rather than storing all the sensor data or as-built BIM data with original data format. As a result, the statements are included in the block header along with the previous block information, Merkle root, which is a summary of all the transactions in a block and a time-stamp in the blockchain (Fig.1-(d)). The block header is encrypted with a digital signature and hash value through the SHA-256 algorithm which is a cryptographic hash function to convert the block into a string of 256 bits (Fig.1-(e)). The block header, digital signature, and hash are combined to generate a new block and then newly chained to the previous blockchain. All project participants access and verify such blockchain traceably so that they can share the project-related information transparently (Fig.1-(f)).

4.2. System architecture

The system architecture of the suggested framework is shown in Fig. 2. The system architecture shows detailed data transaction flow and utilized platforms in detail. Also, this architecture shows how the blockchain executes all transactions in the digital twin in a safe and trustworthy process, which makes the compliance statement provided by the digital twin reliable enough to be used for contract execution

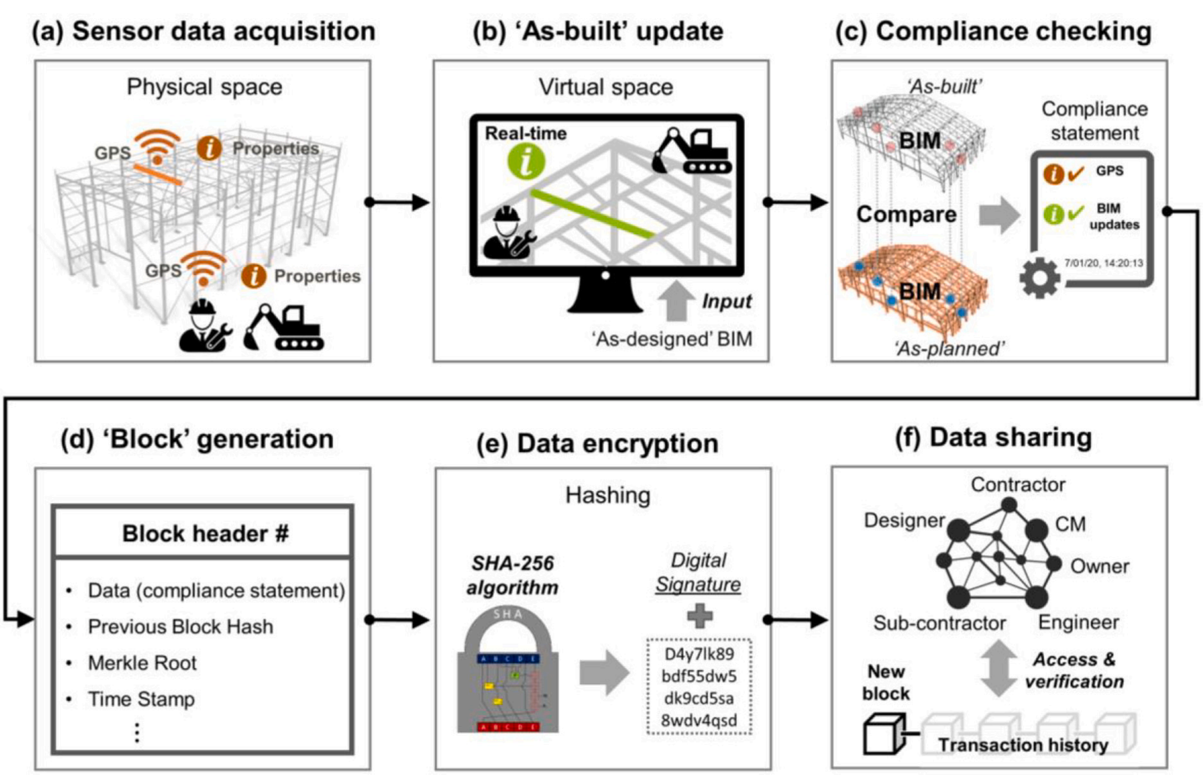


Fig. 1. Integrated digital twin and blockchain framework.

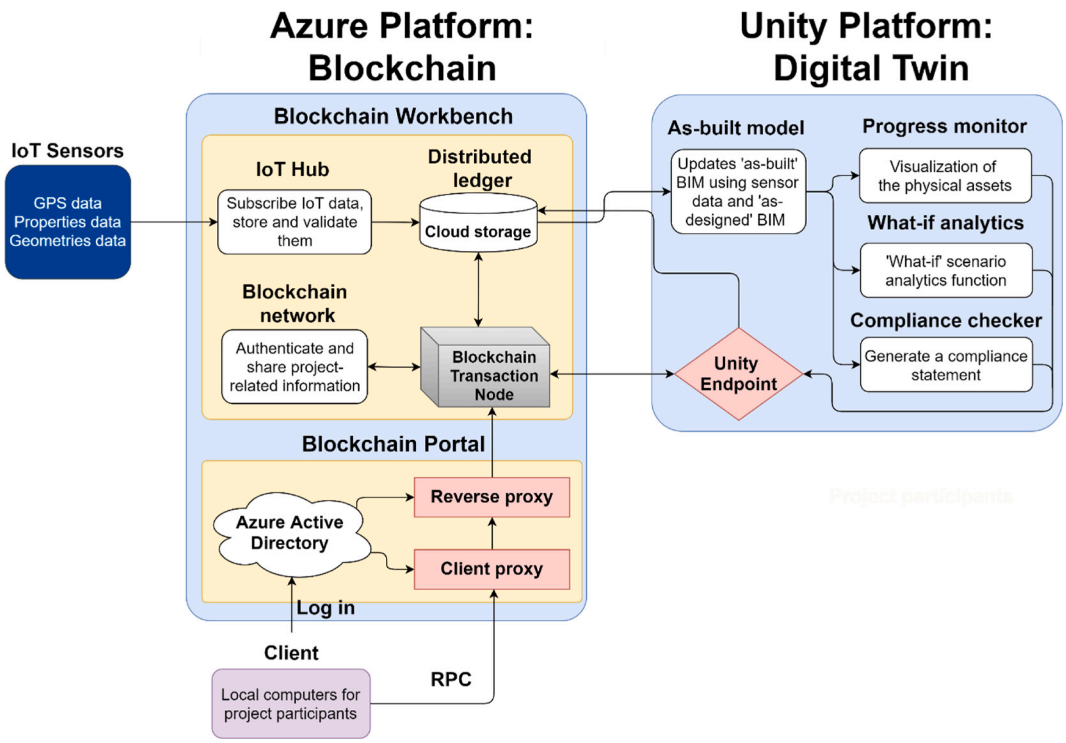


Fig. 2. System architecture of integrated digital twin and blockchain.

and/or payment.

IoT sensors collect real-time sensory data (e.g., GPS) from the construction site and deliver it to the blockchain workbench. Azure (Azure; Microsoft, Seattle, Washington, USA), a cloud service platform, is adopted for the blockchain platform because it provides all modules for blockchain service including IoT hub, web server, cloud storage, and blockchain network. Azure blockchain uses the Ethereum-based Quorum ledger protocol designed for the high- speed processing of private transactions within a group of authorized participants. Specifically, the IoT hub of Azure subscribes and validates IoT sensor data. This sensor data is stored in the distributed ledger, which is a separate big database which can be accessed by any node in the blockchain. The distributed ledger is not designed for real-time data sharing, but it can store all sensor data historically for back up, and the data is transferred to the digital twin platform.

The digital twin was built on Unity (Unity; Unity Technologies, San Francisco, California, USA). Unity is one of the game engines, which runs on the C# and .net framework. Unity supports plug-ins for BIM data transfer and sensor synchronization, real-time visualization, thus many customized function modules needed for digital twin can be implemented on Unity. For example, Unity enables immersion into an as-built BIM for progress monitoring by subscribing to the sensor data and as-designed BIM. Three function modules are implemented in the digital twin platform namely; progress monitor, what-if analytics, and compliance checker. Progress monitor is a visualization of current physical assets that ensure that project participants are on the same page and understanding for the steps that they must take to complete the project as planned. What-if analytics is a simulation tool to anticipate potential issues and future construction scenarios to take proactive action. For example, contractors may find alternate building materials when specific building materials are not available in the market, hence they assess the alternate cost and schedule plans. The compliance checker is a tool to generate compliance statement by comparing as-planned BIM and as-built BIM for subsequent contract execution and/or payment. Any data from these three modules are connected to the distributed ledger and/or blockchain transaction node through Unity endpoint for data storing and sharing respectively.

The distributed ledger can store all up-to-date data from the digital twin historically regardless of their file size, but it is not designed for real-time data sharing. On the other hand, the blockchain transaction nodes are responsible for acting as a communication point of participants and sharing blockchain transactions in near real-time. The transaction node is a ‘full’ node meaning that it contains a full copy of the transaction history of the blockchain for verifying all of the transactions and blocks. Since only designated project participants constitute the few nodes in the construction project and share the compliance statements, the entire transaction history (i.e., full node) can be stored in the cloud and shared in near real-time. The nodes are governed by assigned project participants who logged into Azure Active Directory with their personal computer by way of remote procedure call (RPC) which is a protocol that one program can use to request a service from a program located in another computer on a network. The nodes can create a transaction to the blockchain network as well as can access distributed ledger and Unity. The blockchain network is a peer-to-peer network, designed only for sharing important updates traceably in near real-time. Thus, all data transaction from the sensor to the digital twin is stored in the distributed ledger for back-up, and important updates essential for fast decision-making can be selectively shared in the blockchain network.

This architecture shows that both the sensor data directed toward the digital twin and all data transactions occurring within the digital twin go through the blockchain platform. This is designed to ensure that all data from the sensor to the digital twin are traceably stored and shared in the blockchain platform, which can make all data transactions in the digital twin trustworthy.

5. Case study

To demonstrate that the developed framework operates as intended, a case study is presented in this section. In the case study, the authors created a virtual robotic construction project where industrial robots transport and assemble prefabricated (prefab) concrete bricks to construct a small-scale mock-up bridge. In this robotic construction, robots are synchronized with virtual robots in the digital twin via robot operating system (ROS) which is a set of software libraries and tools that can be used to control motion of real robots [46]. Thus, high-fidelity simulation for robotic construction is possible in the digital twin. Also, the robotic construction allows for precision and accuracy throughout all construction processes, which ensures quality, and thus helps the digital twin perform more reliable compliance checking. With this reliable compliance checking, the authors can solely focus on the performance of information traceability, the aim of this framework.

In this case study, the authors intend to verify that the evolving digital twin over time which includes big file sizes of BIM can generate a compliance statement that can be shared immutably and traceably via a blockchain network. This verification would also confirm that the digital twin's historical data can be stored without overwriting issues and traceably shared in a blockchain network with limited storage, thus demonstrating the proposed framework's potential.

5.1. Test scenario

The test scenario for verification is that two industrial robots convey prefab interlocking bricks from the stockyard to an assembly location, and assemble them to construct a small-scale mock-up bridge. The bridge consists of a total of 49 bricks with 4 different types, and their as-planned BIM and assembly sequence of the bricks are planned in advance, as shown in Fig.3 [47]. The original file size of the as-planned BIM was 876 megabytes.

In this test scenario, the authors assumed that virtual hypothetical sensors that can track locations (e.g., GPS and RFID) are attached to each brick and transmit the brick's locations and types to digital twin in real-time. Each time a brick is assembled, the digital twin checks for compliance to ensure that the location and type of the brick comply with the as-planned BIM (Fig.4). For the simplicity of testing, we checked for compliance only with the location and type of brick, but other compliances (e.g., building codes or standards) can also be checked in the same manner if needed. The results of the checking are then documented as a compliance statement, which is stored in a new block, hashed, and encrypted with signature, transmitted to the blockchain, and then shared in the blockchain network which consists of 10 project participant nodes (e.g., owners, contractors, and subcontractors).

Once participant nodes receive a new block, they authenticate the block's hash with their signature. If their signature matches the signature of the hash, such a node can decrypt the block and consent to chain the new block to the current blockchain (new blockchain generation). Each block generation is verified by a consensus among the majority of participants in the network [48]. In other words, when more than 51% of nodes consent to the new block's generation, it is chained and shared among all nodes regardless of the others' opinions [6,49]. In order to demonstrate this process of consensus, the authors assumed 3 of the 10 blockchain nodes do not have a valid signature.

To analyze the traceability of data communication, the authors developed a dashboard that records all data transactions as shown in Fig.5. This dashboard is used both for tracing data transactions in the digital twin and data transactions among different nodes in the blockchain. Any updated activities in the integrated digital twin and blockchain framework during the case scenario show up here in terms of when and who changed what and how.

5.2. Results

49 compliance statements, each with a file size of about 0.5 kilobytes (Fig.6), were created in the digital twin for 49 brick assembly tasks. 49 blocks were also generated to build a blockchain, which includes all project-related information in the case scenario. Although a 876-megabyte BIM was used as input for the digital twin, blockchain only shares a 0.5-kilobyte document that includes all the participants' records. Each time a new block generation is requested, it is sequentially delivered to 10 blockchain transaction nodes, and be authenticated by each node with their signature as shown in Fig.7.

If a node has a valid signature, it consents with the block generation and the consent time is recorded (Fig.6 shows the average consent time for 49 blocks). At first, nodes #4 and #5 received the request from node #1 and they consented on it, while nodes #3 and #7 are not able to consent the request because they do not have a valid signature. The reason for not having a valid signature is that they (nodes #3 and #7) are assumed to modify previous blocks. If a node modifies the previous block data arbitrarily, its current hash value and signature are changed accordingly so that such a node cannot participate in the consensus

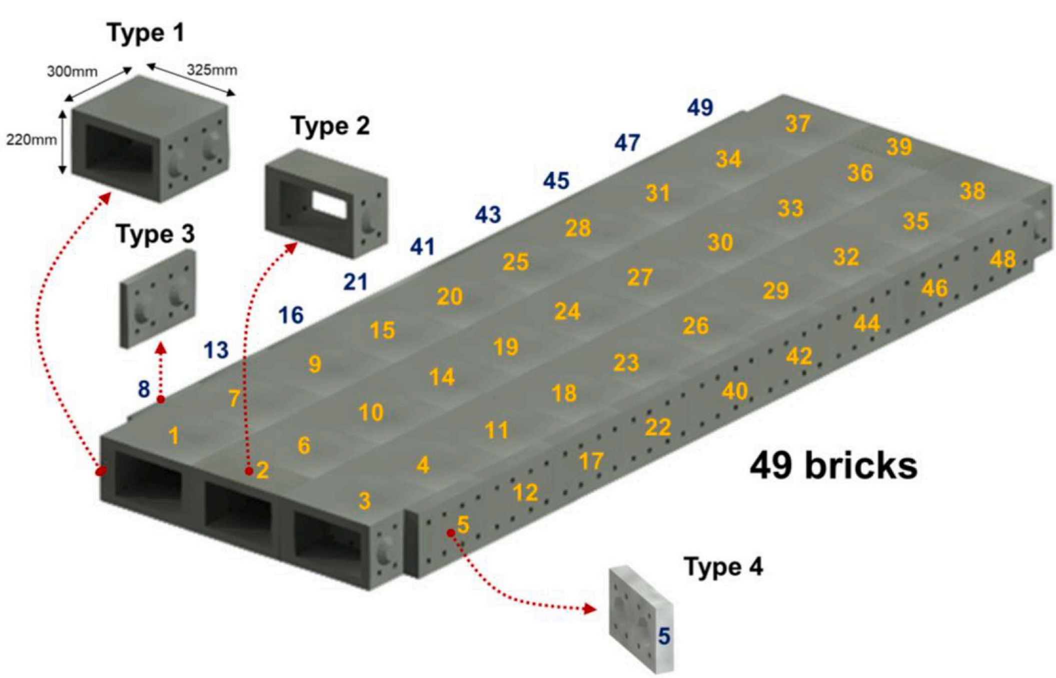


Fig. 3. As-planned BIM of mock-up bridge and its construction sequence.

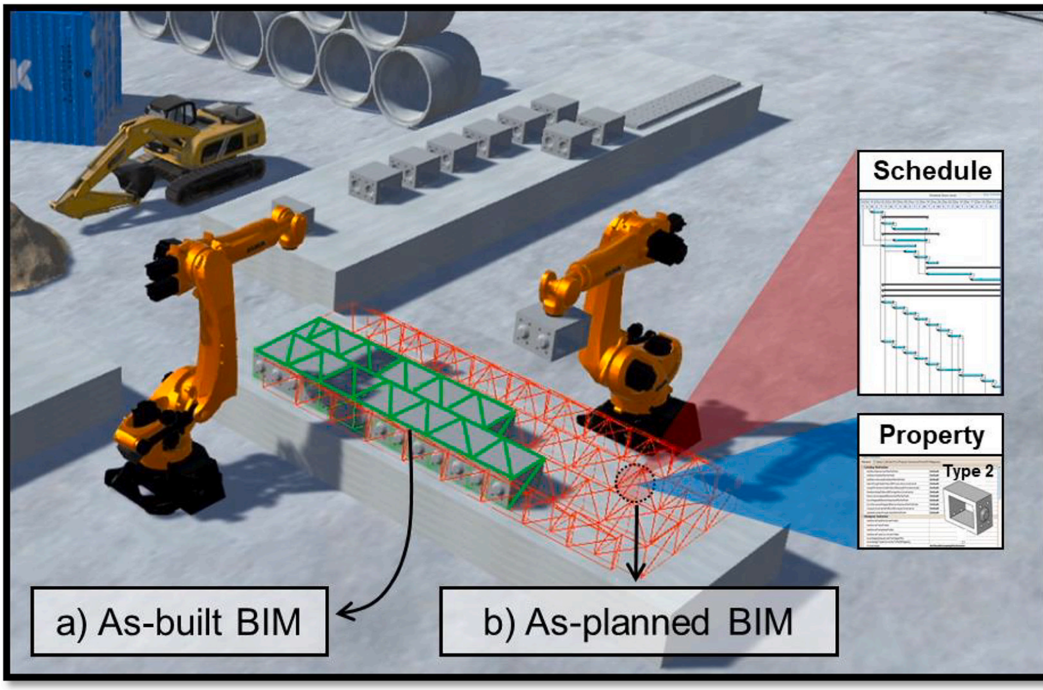
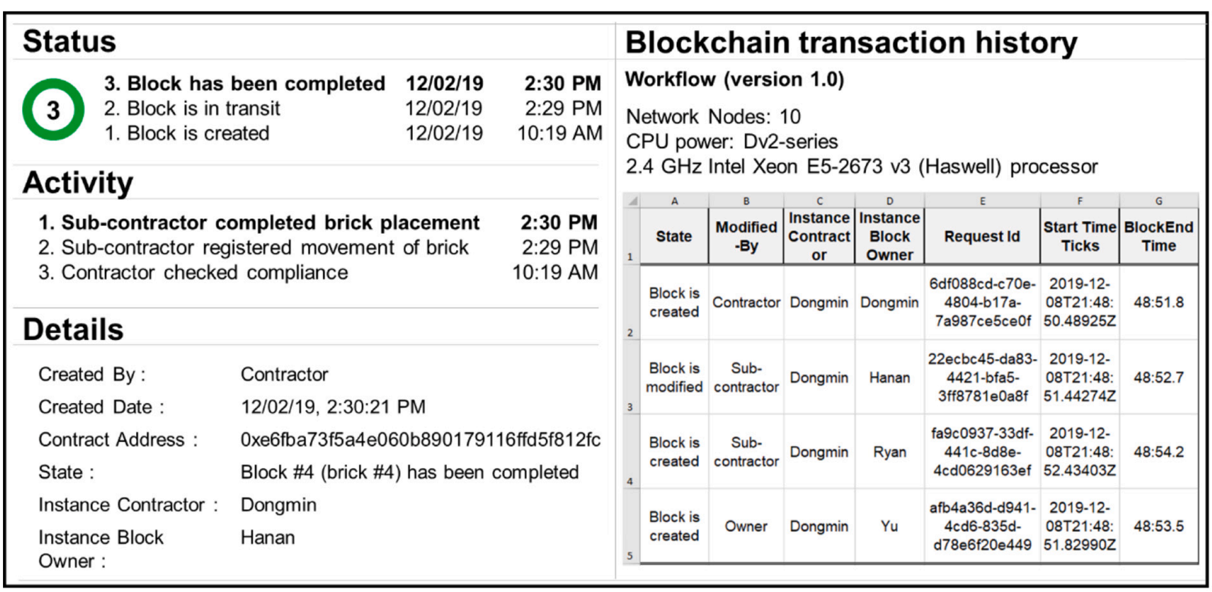


Fig. 4. As-built and as-planned BIM in digital twin for compliance checking.



Status

3

3. Block has been completed	**12/02/19**	**2:30 PM**
2. Block is in transit	12/02/19	2:29 PM
1. Block is created	12/02/19	10:19 AM

Activity

1. Sub-contractor completed brick placement	**2:30 PM**
2. Sub-contractor registered movement of brick	2:29 PM
3. Contractor checked compliance	10:19 AM

Details

Created By :	Contractor
Created Date :	12/02/19, 2:30:21 PM
Contract Address :	0xe6fba73f5a4e060b890179116ffd5f812fc
State :	Block #4 (brick #4) has been completed
Instance Contractor :	Dongmin
Instance Block Owner :	Hanan

Blockchain transaction history

Workflow (version 1.0)

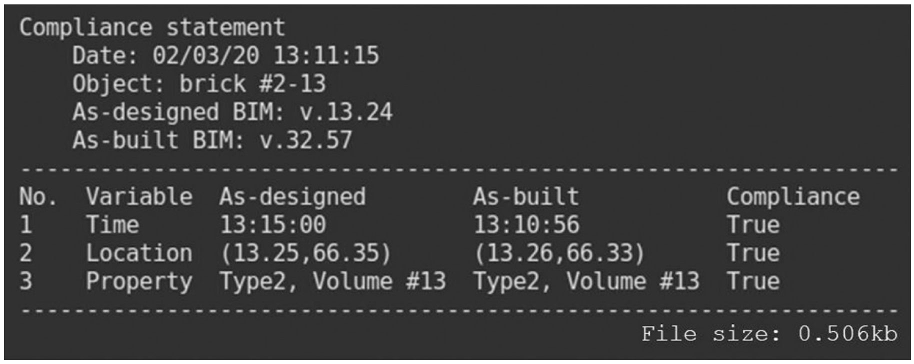
Network Nodes: 10
CPU power: Dv2-series
2.4 GHz Intel Xeon E5-2673 v3 (Haswell) processor

	A	B	C	D	E	F	G
1	State	Modified -By	Instance Contractor	Instance Block Owner	Request Id	Start Time Ticks	BlockEnd Time
2	Block is created	Contractor	Dongmin	Dongmin	6df088cd-c70e-4804-b17a-7a987ce5ce0f	2019-12-08T21:48:50.48925Z	48:51.8
3	Block is modified	Sub-contractor	Dongmin	Hanan	22ecbc45-da83-4421-bfa5-3ff8781e0a8f	2019-12-08T21:48:51.44274Z	48:52.7
4	Block is created	Sub-contractor	Dongmin	Ryan	fa9c0937-33df-441c-8d8e-4cd0629163ef	2019-12-08T21:48:52.43403Z	48:54.2
5	Block is created	Owner	Dongmin	Yu	afb4a36d-d941-4cd6-835d-d78e6f20e449	2019-12-08T21:48:51.82990Z	48:53.5

Fig.5. A blockchain dashboard in Azure.

mechanism. This mechanism excludes the possibility of other nodes sharing incorrect block information by excluding nodes with modified blocks from the consensus mechanism [50]. This modification was intentionally designed by the authors to test the consensus mechanism in the blockchain network. It helps guarantee that all nodes on the blockchain network are synchronized and its transactions are legitimated even when some of the nodes do not have a valid signature. Valid nodes #4 and #5 initiated another network transaction to other nodes. After that, the network nodes #2 and #8 related to nodes #4 and #5 received and responded to the network transactions, and initiated another transaction to nodes #6 and # 9, while node #10 could not participate in this process. Therefore, nodes #1, #4, #5, #2, #8, #6, #9 authenticated all the updates and shared with each other at time 2.41 s. According to the 51% rule of the blockchain, nonvalid nodes #3, #7, and #10 consent on the new transaction and share the same project-related data at 3.42 s (Fig.7).

These results show that compliance statements (Fig. 6) that include essential data for collaboration are generated from the digital twin, and they are stored and shared (Figs. 5 and 7) with timestamps in the blockchain so that project participants can trace them back to audit at any time. Also, the consensus mechanism shows that it can prevent tampered or hacked information from being shared with other nodes. Therefore, project participants can be assured that all project-related information will be shared traceably and immutably.



```
Compliance statement
    Date: 02/03/20 13:11:15
    Object: brick #2-13
    As-designed BIM: v.13.24
    As-built BIM: v.32.57
------------------------------------------------------------------
No.  Variable  As-designed         As-built            Compliance
1    Time      13:15:00            13:10:56            True
2    Location  (13.25,66.35)       (13.26,66.33)       True
3    Property  Type2, Volume #13   Type2, Volume #13   True
------------------------------------------------------------------
                                              File size: 0.506kb
```

Fig. 6. An example of the compliance statement.

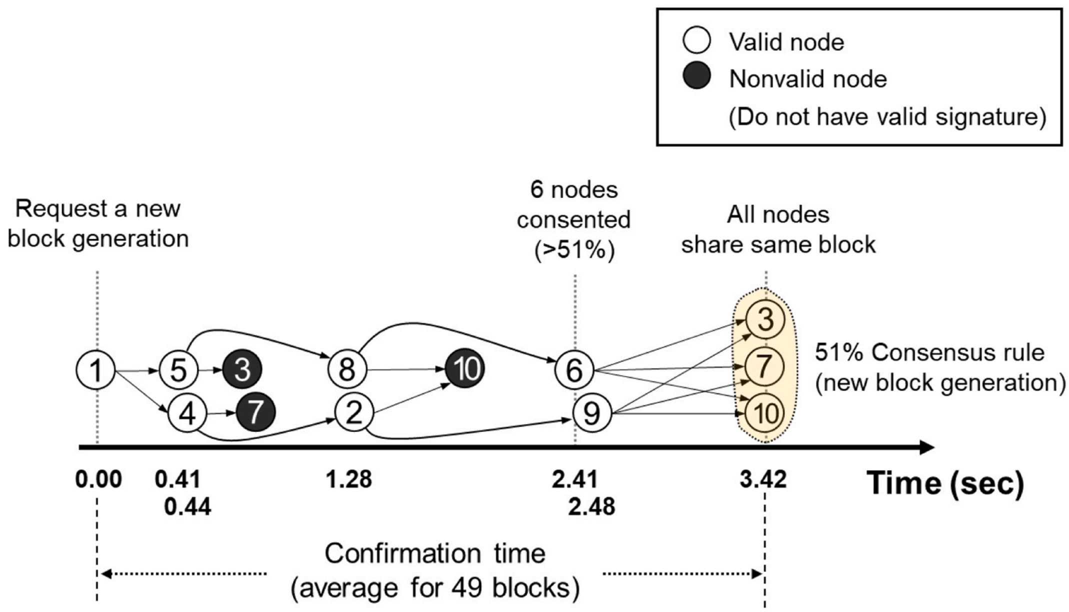


Fig. 7. Results of data sharing test with consensus mechanism among blockchain nodes.

6. Discussion

This paper proposed an integrated digital twin and blockchain framework to secure the data traceability and immutability of a digital twin while overcoming the limited storage of blockchain. The results of our case study showed that any transactions occurring in the digital twin including BIM with a large file size can be shared traceably and immutably in the blockchain network in the form of a compliance statement within 3.42 s. Such traceable and immutable data transactions can create a trust for all data shared among fragmented participants [51]. Such a trust may help the data collected during construction be used for important decision-making (e.g., change order, design change, suspension of works, and purchasing and payment). For example, if project participants can trust a compliance statement from the digital twin, they might consent to change order decisions based on the statement.

If project participants trust in project-related information, it can affect the contract and payment methods of construction projects through a smart contract. The smart contract is automatically executed by a computer code when predefined rules are met, so it eliminates the need for trusted intermediaries (e.g., bank and bonding company) to execute contracts. One of the important benefits of the smart contract would be an instant payment. The smart contract could vastly speed up the progress payment process. All project participants would agree in the contract to construction milestones and associated payments. Once a compliance statement is verified by the participants, payments could automatically be enforced. This payment process would be instant and continuous not monthly or quarterly, so project participants can avoid any payment delay which spurs conflicts and disputes. One potential application is to make payments through cryptocurrencies such as Bitcoin, Ripple XRP, and Ethereum. Such cryptocurrencies run on a blockchain network that allows them to operate without the need for a central bank. The cryptocurrency supports fast cross-border financial transactions, which is beneficial for construction projects that consist of many different companies from all over the world. Also, the transaction fee of cryptocurrency is comparatively lower than current centralized banks [52], thus it is suitable for progress payment which needs plenty of separated payments.

Such traceable data communication also has good potential benefits for supply chain management in a construction project. Especially in the prefabricated construction method where off-site products (e.g., concrete bricks) of a structure are built off-site and shipped to a construction site for installation on that site like the case project, a supply chain becomes particularly important because the performance of on-site assembly can be maximized when such off-site products are delivered to the site on time [53]. However, the supply chain often spurs many conflicts and disputes caused by a fragmented contract process among participants. One of the major causes of cost inefficiency or time delays in large construction projects stem from not having the right material at the right place in the right time. In this regard, if the blockchain improves transparency and builds trust for all supply chains of off-site products, such contract processes can be streamlined through the smart contract. For example, the smart contract can automatically send a signal upstream along the supply chain to stop production/shipping of the off-site products if the on-site assembly schedule is delayed hence saving logistics costs. Moreover, project participants can avoid any delayed payment issues and can make faster contract executions based on the smart contract with reliable supply chain data, which consequently increases its efficiency.

Although this paper demonstrated the feasibility of the suggested framework for traceable data communication, there are several important issues to consider. For example, proof of concept for the blockchain in this paper was a 'private' blockchain, within which only permitted project participants are able to participate because construction projects contain a significant amount of sensitive data, such as copyrights for building design, pricing, legal agreements, and financial data [54]. Private blockchains restrict access to the network and require permission for a participant to view and transact on the network, which ensures confidentiality for the sensitive data. In addition, a private blockchain has high transaction performance with few participants, thus a shorter time frame is required to gain consensus for a new block than would be offered by a public blockchain, which is completely open and allows anyone to participate in the network [55]. Therefore, a private blockchain ensures good 'scalability' (i.e., ability to cope with the influx of a large number of transactions at a time) [56], especially in the construction industry, where only authorized project participants in a project can create transactions. However, such private blockchains consist of only a few trusted nodes authorized by a central entity so that it is easier to gain control over the network by any bad actor [55]. For this reason, private blockchain has inherent 'security' risk in terms of hacking and data manipulation as well as is less 'decentralized' in terms of network governance. Many blockchain development projects are facing these issues, which are collectively referred to as 'blockchain trilemma': no ledger can satisfy all three main properties, such as security, scalability, and decentralization, simultaneously [57,58].

The authors suggest future research in construction blockchain should consider this trilemma. In other words, a blockchain should be developed in a way that maximizes 'decentralization' and 'security' as possible under conditions that can secure good 'scalability' for the construction project. In order to achieve that aim, characteristics of data communication in the construction project such as the size of transaction data, number of transactions, update frequency, number of project participants (nodes), and data access level for participants should be quantitatively analyzed. Then, considering the characteristics, a more decentralized and highly secured blockchain can be developed while avoiding any scalability issue. For example, the 'decentralization' can be strengthened by allowing another reliable external player nodes can access the private blockchain only for verifying transactions. Such players prevent several nodes from having absolute control over the transactions. Also, the 'security' can be enhanced by using a higher security metric (e.g., high hash rate, longer signatures, and complex cryptography algorithms). The important point here is that both 'decentralization' and 'security' can be improved within a range that does not cause any 'scalability' issue by considering both transaction performance of a blockchain platform and characteristics of the data communication in the construction project. In this way, a 'hybridized' blockchain that combines and balances the advantages of both public and private blockchain can be developed in the future to achieve better data communication for construction projects.

7. Conclusion

The authors proposed and implemented the integrated digital twin and blockchain framework to selectively store and share important project-related information traceably. A blockchain dashboard is created to track and analyze all data transactions in a case project. Results indicate that the digital twin can generate compliance statements in near real-time and that they can be traceably and immutably shared among ten fragmented project participants without intermediaries within 3.42 s via the limited storage of a blockchain network. The main contribution of this paper is to show how an integrated digital twin and blockchain framework can help to secure traceable and immutable data communication among project participants. The traceable and immutable data communication can secure trust for project-related data. Such accountable data can vastly speed up subsequent contract execution, payment, and even decision-making (e.g., submittal, change order, and design change), which can ultimately facilitate better collaboration among fragmented project participants.

Declaration of Competing Interest

None.

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