



Research
Engineering Management—Article

A Blockchain-Based Life-Cycle Environmental Management Framework for Hospitals in the COVID-19 Context



Botao Zhong ^{a,b}, Han Gao ^{a,b,c}, Lieyun Ding ^{a,b,*}, Yuhang Wang ^{a,b}

^a National Center of Technology Innovation for Digital Construction, Huazhong University of Science and Technology, Wuhan 430074, China

^b School of Civil and Hydraulic Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

^c Department of Civil and Building Systems, Technische Universität Berlin, Berlin 13156, Germany

ARTICLE INFO

Article history:

Received 12 March 2022

Revised 13 May 2022

Accepted 16 June 2022

Available online 7 October 2022

Keywords:

Blockchain

Environmental management

Nosocomial infection control

Work quality management

Life-cycle traceability

ABSTRACT

During the coronavirus disease 2019 (COVID-19) emergency, many hospitals were built or renovated around the world to meet the challenges posed by the rising number of infected cases. Environmental management in the hospital life cycle is vital in preventing nosocomial infection and includes many infection control procedures. In certain urgent situations, a hospital must be completed quickly, and work process approval and supervision must therefore be accelerated. Thus, many works cannot be checked in detail. This results in a lack of work liability control and increases the difficulty of ensuring the fulfillment of key infection prevention measures. This study investigates how blockchain technology can transform the work quality inspection workflow to assist in nosocomial infection control under a fast delivery requirement. A blockchain-based life-cycle environmental management framework is proposed to track the fulfillment of crucial infection control measures in the design, construction, and operation stages of hospitals. The proposed framework allows for work quality checking after the work is completed, when some work cannot be checked on time. Illustrative use cases are selected to demonstrate the capabilities of the developed solution. This study provides new insights into applying blockchain technology to address the challenge of environmental management brought by rapid delivery requirements.

© 2022 THE AUTHORS. Published by Elsevier LTD on behalf of Chinese Academy of Engineering and Higher Education Press Limited Company. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

1. Introduction

The coronavirus disease 2019 (COVID-19) that started in 2019 has spread rapidly to become a global pandemic. During the pandemic of the new coronavirus, many patients developed into severe cases and required hospitalization [1]. Individuals who require hospitalization have higher viral loads than other patients, increasing the risk of hospital cross-infection [2]. A contaminated environment is highly significant in pathogen transmission. Thus, maintaining a safe and clean hospital environment is critical for breaking chains of transmission and preventing nosocomial infection during the pandemic. According to the World Health Organization (WHO) Pan American Regional Office, more than 570 000 healthcare workers (HCWs) were infected and 2 500 around the world died during the pandemic before September 2020 [3]. In some healthcare facilities, HCWs had a tenfold higher risk of infection than non-HCWs [4]. An analysis showed that over one in ten

infected cases in the UK's first pandemic wave were hospital-acquired [5]. Air and surface contamination by pathogenic biological aerosols is recognized as a major potential route of hospital cross-infection [6].

Environmental management for infection prevention in COVID-19 healthcare facilities requires interdisciplinary cooperation. Traditional environmental infection control strategies, including personal protective equipment (PPE) usage and scheduled disinfection and cleaning procedures (i.e., disinfection of indoor air and object surface cleaning), have received the most attention in the literature [7–9]. As a crucial way to combat airborne pathogens, engineering control measures such as ventilation, air filtration, indoor pressure gradient control, and avoidance of recirculation have also played a key role in environmental safety [10–12]. A previous study found that the addition of engineering infection control measures without altering the traffic and workflow patterns of HCWs can reduce healthcare-associated infections by 45% [13]. Both traditional environmental infection control strategies and engineering controls are conducted during the operation stage of healthcare facilities. During the COVID-19

* Corresponding author.

E-mail address: dly@hust.edu.cn (L. Ding).

pandemic, new infectious disease hospitals have been built to cope with the increasing need for hospital-based healthcare services during a surge of patients, and general hospitals have been retrofitted to provide negative-pressure isolation spaces. The effectiveness of engineering control measures in the operation stage is directly affected by design and construction factors such as designs for the ventilation and air conditioning system, healthcare unit layout design, equipment installation, construction quality of isolation wards, and so forth. For example, badly designed isolation rooms with, for example, inadequate air-change rates can increase the risk of airborne transmission [14]. To sum up, the success of nosocomial infection control requires integrated and targeted measures in the design, construction, and operation stages.

During the emergency of a pandemic, medical workers, states, and local governments must prepare for an increase in critically ill patients and be ready to act quickly. Under such circumstances, the work of building new infectious disease hospitals or expanding negative-pressure wards in existing hospitals needs to be finished in a short time. In such an urgent situation, some work cannot be checked as carefully as usual, and there might be a lack of work quality control for activities in the design and construction stages, which may increase infection risk in the operation stage. A similar situation occurs in the operation stage of the hospital. During the operation of the hospital, many medical workers in the COVID-19 pandemic frontline do not have enough requisite expertise and context about nosocomial infection prevention [15]. Studies show that, in 258 cleaning cases reported in a hospital, the rate of compliance with disinfection measures was only 35% [16]. Meanwhile, a lack of maintenance or the unexpected failure of devices in negative-pressure wards can lead to the spread of pathogens to neighboring areas. Viral RNA was detected on 114 of 218 (52.3%) surface samples and in 14 of 31 (45.2%) air samples in hospitals during the peak of the COVID-19 pandemic in London, UK [17]. Thus, whether in the design and construction stages or in the operation stage of hospitals, strict compliance with infection control procedures is of key importance in reducing hospital-acquired infection. Considering the need for the rapid completion of new hospitals or hospital renovations brought by a surge in infection numbers, compliance with infection prevention procedures in the design, construction, and operation stages cannot be checked on time and must be checked later. To ensure the fulfillment of nosocomial infection control, the critical work process needs to be reliably recorded in order to support accountability and auditability.

Blockchains are an emerging technology that can improve data security, transparency, and traceability and that have shown potential in information-tracking applications such as supply-chain management [18,19] and healthcare records management [20,21]. They can ensure that data is protected against loss, corruption, and manipulation. Existing studies have explored how blockchain technology can help the healthcare system in combating the COVID-19 pandemic. Most previous studies have focused on blockchain applications for early warning and vaccination management, including contact tracing [22–24], pandemic surveillance and reporting [25–27], verifiable vaccine certificates [28], electronic medical records management [29], and vaccine supply-chain tracing [30]. However, no study has used blockchain technology in hospital environmental management to prevent nosocomial infection under the COVID-19 pandemic. During the rapid delivery of a hospital project under the extreme circumstances of a pandemic, many processes may not be under strict quality supervision due to the requirement for speed; however, mistakes in design, construction, and operation activities may increase the risk of nosocomial infection. Given this background, this study aims to answer two research questions:

- How can a blockchain-based system help nosocomial infection prevention in newly built or renovated hospitals?

- How can blockchain technology address work inspection challenges to help with environmental management during an accelerated work mode?

To answer these research questions, this paper presents a blockchain-based life-cycle hospital environmental management framework to ensure the traceability and accountability of work procedures. With the nonrepudiation feature of blockchains, work can be checked later if it cannot be checked on time during an urgent situation. The blockchain's immutable process information storage can improve the sense of responsibility of different participants, help reduce the risk of data manipulation, make the work quality more transparent, and ultimately help to ensure the safety of the hospital environment. In addition, the smart contract embedded in a blockchain can monitor the fulfillment of the project's conditions and support real-time environmental monitoring and equipment maintenance by sending notifications to hospital staff. The major contributions of this study are as follows: First, this study fills a research gap in the application of blockchain technology in hospital environmental management by developing a blockchain-based nosocomial infection control solution. Second, this study presents a new quality management workflow enabled by blockchain technology to address the challenge of quality inspection during an accelerated work mode.

The rest of this paper is organized as follows. In [Section 2](#), we review the literature related to this study and define the research gap; we then demonstrate the reason for choosing a consortium blockchain in this study. [Section 3](#) describes the conceptual model and system architecture of the proposed blockchain-based framework, and [Section 4](#) illustrates blockchain-enabled key applications for environmental quality management in the hospital life cycle. We also present illustrative use cases to provide examples of how the proposed framework can benefit the environmental management of hospitals. [Section 5](#) analyzes the performance of the proposed scheme, while [Section 6](#) discusses the managerial implications and theoretical implications. Finally, [Section 7](#) presents the conclusions.

2. Related work

2.1. Blockchain-based healthcare applications for COVID-19

The concept of a blockchain was developed by Satoshi Nakamoto [31] in 2008 to solve the double-spend problem of cryptocurrencies. A blockchain is a distributed ledger that chronologically and securely records all data shared among all participants in a peer-to-peer (P2P) network [32]. Nodes on the chain will propagate transaction information on the P2P network, with each node having a copy of the ledger [33]. The P2P propagation mechanism ensures that records cannot be tampered with. Blockchain technology was originally proposed to solve the security and privacy issues of digital currency transactions (i.e., Bitcoin), but the application of a blockchain is not limited to digital currencies. The technology also has the potential to generate disruptive applications for different industries.

Several blockchain studies examine infection control in the healthcare domain, aiming to solve different challenges in the COVID-19 pandemic. The related studies are listed in [Table 1](#) [22,23,25,26,30,34–38], and are categorized into multiple domains (e.g., pandemic control and surveillance, health and immunity certificates, etc.). The first type of blockchain application is pandemic control and surveillance. For example, Ouyang et al. [25] proposed a framework for collaborative early warning for COVID-19 based on a blockchain and smart contracts to reduce the risk of decision-making errors during early warning. Lee et al. [26] developed a blockchain-based architecture that can be used for

Table 1
Blockchain-based healthcare applications for COVID-19.

Category	Related topics in the field	Research focus	Publications	
Healthcare	Pandemic control and surveillance	COVID-19 early warning	[25]	
		Global infectious disease surveillance and infected case tracking	[26]	
	Health and immunity certificates	Verification of tamper-proof test results	[34]	
		Medical supply-chain management	Vaccine supply management	[30]
			Medical equipment supply-chain management	[35]
	Contact tracing	Supply-chain management of ventilators and PPE	[36]	
		Privacy-preserved contact tracing	[22]	
		Contact information sharing	[23]	
	Electronic medical records	Patient health information sharing	[37]	
		COVID-19 patient reports sharing	[38]	

information retrieval on disease transmission in order to achieve global infectious disease surveillance and infected case tracking. The second type of blockchain application is related to health and immunity certificates. Eisenstadt et al. [34] proposed a blockchain framework combined with an encryption algorithm to realize the verification of tamper-proof test results in a mobile application. The third type of blockchain application is about supply-chain management for vital supplies such as vaccines, PPE, and medications [39–43]. Another important application scenario is contact tracing. Bandara et al. [44] developed a blockchain-empowered COVID-19 contact tracing platform that can notify people who are near positive cases while preserving the privacy of the infected people at the same time. The above studies have shown the potential of blockchain technology for helping in the fight against the pandemic in the healthcare domain. These studies have covered many aspects related to containing the spread of a pandemic. Nosocomial infection prevention is a critical aspect of controlling a pandemic; however, no study as yet has discussed the role of blockchain technology in nosocomial infection prevention.

2.2. Blockchain technology in project management

A significant number of disputes and litigations can occur in a project [45]. Blockchain technology has attracted a great deal of attention in project management, as it can help in many aspects of a project such as trust, information sharing, and process automation. Several researchers have begun to study the technical characteristics of blockchains and their potential applications in project management. Turk and Klinc [46] illustrated the challenges in engineering management and pointed out that a blockchain can improve the reliability and trustworthiness of construction logs, works performed, and material quantities recorded. Li et al. [47] stated that the properties of blockchains, such as immutability, traceability, and transparency, can lead to better accountability and auditability, which will enable the industry to manage resources better while reducing costs, project duration, and payment disputes.

Aside from theoretical analysis, some scholars have studied how blockchains can be implemented into specific management processes. The completion of a project is primarily a collaborative effort between different participants, and liability control is an essential task in process management. Pradeep et al. [48] developed a blockchain-based design workflow that aims to improve design liability control in the design process. Sheng et al. [49] developed a blockchain-based construction quality management platform to provide error traceability in construction activities. Lu et al. [50] proposed a blockchain-based framework to realize information sharing, tamper proofing, and traceability in the supervision of construction works.

Furthermore, blockchain applications are implemented in construction supply-chain management [51,52] and project delivery

management [53]. Although an increasing number of blockchain-based applications have been proposed to deal with various engineering management problems, few studies have considered how blockchains can help engineering management in emergency situations. Many emergency hospitals have been built, transformed, or expanded all over the world to meet the rapidly increasing demand for medical treatment in the context of COVID-19. Schedule, cost, and quality are known as the “iron triangle” in project management [54]. The compressed schedule of emergency hospital projects has brought great challenges to quality management [55]. A case study of the Huoshenshan and Leishenshan Hospital projects in Wuhan indicates that the sharp schedule compression resulted in less supervision and quality defects; however, it is difficult to deal with these issues within a limited time [56]. This study aims to employ blockchain technology to address the quality supervision challenges brought by rapid delivery requirements during the COVID-19 emergency. A blockchain-based environmental management framework is developed, which can provide an immutable work record storage so that work that cannot be checked on time can be checked later.

2.3. Selection of a blockchain system

At present, many types of blockchain systems exist; these can be divided into the following three categories according to the degree of decentralization and transparency: public, private, and consortium blockchains [57]. A comparison of the three types of blockchains is shown in Table 2.

- **Public blockchain:** A public blockchain is usually regarded as a permissionless blockchain [58]. This blockchain type is open to anyone who wants to join the network. Anyone in the network may view, read, and write data on the public blockchain. The blockchain is completely decentralized, and no third-party management system exerts control over the blockchain network [59]. Transaction data that are confirmed

Table 2
Comparison of public, private, and consortium blockchains.

Blockchain type	Public	Private	Consortium
Access level	Anyone	Single organization	Multiple organizations
Authority	Highly decentralized	Partially decentralized	Partially decentralized
Transaction reading/writing	Anyone	Single organization	Selected multiple organizations
Consensus mechanisms	Distributed consensus (PoW, PoS)	Voting/multi-party consensus	Voting/multi-party consensus
Speed	Slow	Fast	Fast
Scalability	Low	High	High

and uploaded to the blockchain cannot be changed. Well-known public chains mainly include Bitcoin and Ethereum [60,61]. These public blockchain platforms have relatively slow transaction speeds because they require time for all nodes to reach a consensus for each transaction [62,63]. Proof of work (PoW) and proof of stake (PoS) [64] are the most commonly used consensus mechanisms in public blockchains. Although they can enhance the reliability of transaction confirmation on the blockchain, they also reduce the transaction speed. For example, Bitcoin processes roughly seven transactions per second (tps), whereas Visa can complete more than 20 000 tps [47].

- **Private blockchain:** A private blockchain network is limited to users who have been invited or permitted to join [62]. The private chain is not fully decentralized, is managed by a specific subject, and requires participants to apply for permission to read and write to the blockchain [65]. The data on the network are not visible to the public and can only be viewed by the participating nodes. Compared with a public blockchain, a private blockchain provides more data privacy protection. A private blockchain has fewer nodes, resulting in a faster transaction speed. Private blockchains are more suitable for situations in which information only needs to be shared by a limited number of participants.
- **Consortium blockchain:** A consortium blockchain is partly a private blockchain solution, but it is managed and maintained by multiple organizations instead of a single-owner organization [66]. This blockchain type has some advantages similar to those of private chains, such as fast transaction confirmation, low storage cost, and good privacy protection. Nevertheless, as a semi-decentralized blockchain, it is under the supervision of a handful of predefined nodes to prevent monopoly [67]. The management nodes in a consortium

blockchain can create channels so that blockchain members can communicate with each other. In addition, different channels can be set for different business activities to achieve transaction data isolation. A consortium blockchain is a better solution for a setting in which multiple institutions cooperate in the same industry and need a trusted environment.

In the scenario of a hospital project, there are many different organizations involved, such as material suppliers, construction managers, designers, hospital staff, and so forth. Project documents such as design files and construction records have strict privacy protection requirements. The participants are assigned defined roles to perform only permitted activities in the project process. Hence, this study employs a consortium blockchain to build the system architecture. In addition, compared with public blockchains, consortium blockchains are less expensive to implement because they consume less electricity, as no mining tasks are involved.

3. A blockchain-based hospital environmental management framework

The fulfillment of critical infection control precautions in the design, construction, and operation stages is vital for the environmental safety of the hospital and must be critically monitored. In the following sections, a conceptual framework and system architecture are proposed to help improve the traceability of key process information related to hospital environmental management during an accelerated work mode.

3.1. Conceptual model of the proposed blockchain-based framework

The conceptual model of the proposed blockchain-based framework is shown in Fig. 1. The model consists of five key

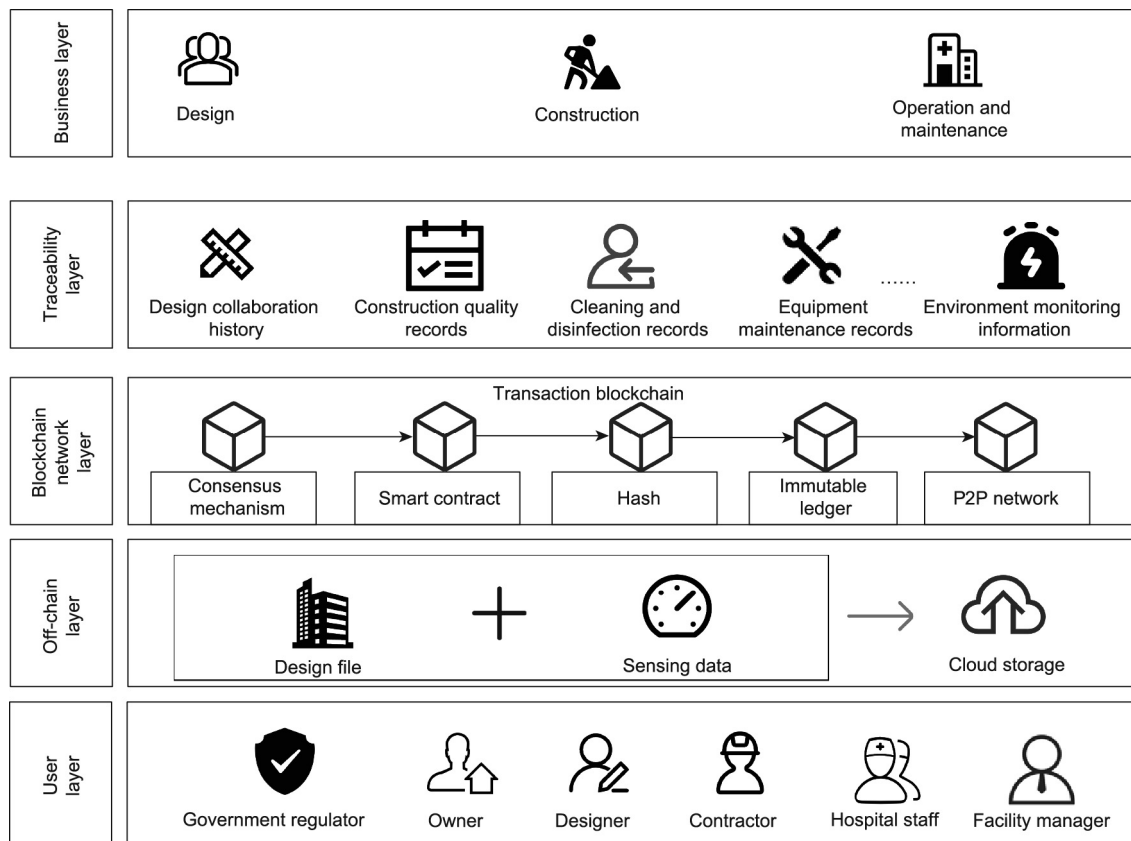


Fig. 1. Conceptual model of the proposed framework.

components: the business, data traceability, blockchain network, off-chain, and user layers.

The *business layer* describes key activities throughout the entire life-cycle of the infectious disease hospital project and includes design, construction, operation, and maintenance. Each stage produces information related to the key infection control measures. The related information must be digitalized in blockchain transactions to make the work quality traceable.

The *data traceability layer* collects key process information in the project life cycle related to hospital infection prevention. This layer manages the life-cycle project information throughout the design, construction, and operation stages. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), the WHO, and the Centers for Disease Control and Prevention (CDC) have issued guidelines and regulations to provide key infection control measures during the design, construction, and operation stages. In the design stage, design files must be checked for compliance with infection control requirements. In the construction stage, it is important to verify that systems are functioning as designed during system commissioning. The key construction quality records must be stored in the system, especially the quality records of negative-pressure wards (e.g., air pressure, airtightness, airflow direction, etc.). In the operation and maintenance stage, Internet of Things (IoT) sensors are used to monitor environmental changes, such as differential pressure meters, temperature, and humidity sensors. In general, this layer aims to collect the environmental-safety-related process information in the project life cycle.

The *blockchain network layer* realizes information exchange between different participants and makes all the hospital life-cycle data transparent and traceable, especially for tracing the source of quality problems. This layer includes a consensus mechanism, smart contract, and hash. First, the consensus mechanism is a multi-party collaboration means of coordinating multiple participants to reach an agreement and ensure that this process is not readily deceived and continues to operate steadily. Second, smart contracts are rules written in certain business logic. When the requirements of the rules are met, the obligations stipulated in the code will be automatically executed. Third, a hash is a cryptographic algorithm used to encrypt transactions. In a blockchain, it can be used to verify digital identities and store encrypted data.

The *off-chain layer* processes the collected data and sends key information to the blockchain network layer. Storage cost on a blockchain is high and unsuitable for storing large amounts of high-frequency data. The design files, IoT data, some large files, and unstructured documents are stored in the cloud server, and the hash values of these files are generated and stored on the blockchain.

The *user layer* contains the participants on the blockchain, covering the entire life cycle of the project. In the present case, blockchain users include government regulators, owners, designers, contractors, hospital staff, facility managers, etc. Each user has different data access rights and participates in different transactions under the framework of smart contracts. The blockchain network allows only authorized users with signatures to write data and start transactions.

3.2. System architecture

This section proposes a system architecture for the blockchain-based life-cycle environmental management system according to the proposed conceptual framework. In this architecture, Hyperledger Fabric (henceforth denoted as Fabric) is selected to implement the blockchain network because of the requirement of data privacy and a permission mechanism. Fabric is an open-source consortium blockchain framework developed under the Linux

Foundation and is one of the most popular and widely known consortium blockchain network frameworks [49]. The system architecture is shown in Fig. 2. The architecture integrates blockchain, IoT, and cloud technologies to develop a decentralized application (DApp) to support environmental management in hospitals. This implementation architecture has been verified by two software developers who are experienced in blockchain technology. The following subsection explains the details of the main components in the system.

3.2.1. Identity management

The participants must register digital identities through the membership service provider (MSP) in the blockchain network. The MSP is a mechanism that enables participants to convert their identities into digital certificates that can be recognized by a permissioned blockchain network. MSP implementation employs a certificate authority (CA) in Fabric to define trusted organizations and set roles for members in the organizations. Each member is assigned a public key and a private key to prove their identity, which in turn determine the participant's access to the records. Stakeholders such as owners, designers, contractors, hospital staff, facility managers, and regulators are regarded as different organizations in the consortium blockchain. The exact authority in relation to the resource and access to records of each peer node in the organization is determined by the MSP. Registration is also required for IoT devices. When a new IoT device is added to the network, a hash value is generated from the product information of the IoT device as registration information. Once sensor data are uploaded to the blockchain, the hash value of the device configuration file is also uploaded to the blockchain, and the trusted IoT data source prevents the data collected at the front end of the IoT sensors from being tampered with and destroyed.

In Fabric, separate channels can be created to isolate transaction data. A channel is used for communication between different organizations. Different members of different organizations can join the channel, with one channel corresponding to one blockchain. Peer nodes in this channel can initiate transactions with each other and share the same ledger. Transactions are invoked by chaincode in Fabric, and a chaincode holds world state and ledger data. For example, we can choose two contractor nodes, one owner node, one government regulator node, and one hospital staff node to form a channel. Each peer node can send records through the web client and invoke the chaincode function in Fabric to initiate a transaction. Once the transaction is verified, the updated transaction information will be broadcast on the channel. This ensures that the information on the channel is synchronized and cannot be tampered with by unauthorized parties.

3.2.2. Off-chain data management

The blockchain-based system architecture can provide participants in the project life cycle with tamper-proof traceability data and an open environment. However, given the distributed storage characteristics of the blockchain, some non-transactional data in the life cycle are too large to be stored on the chain and will reduce the speed of the platform. At the same time, some private data during activities cannot be stored publicly because of privacy issues. In this work, the proposed system architecture provides an off-chain data storage solution.

The proposed system implementation architecture is based on a web client that communicates with the Fabric blockchain network and holds the state of participants on the P2P network. The cloud service processes off-chain data, and Fabric processes on-chain data. All participants must install the client. Participants are assigned with different project data access rights, and life-cycle business data are communicated through the web client.

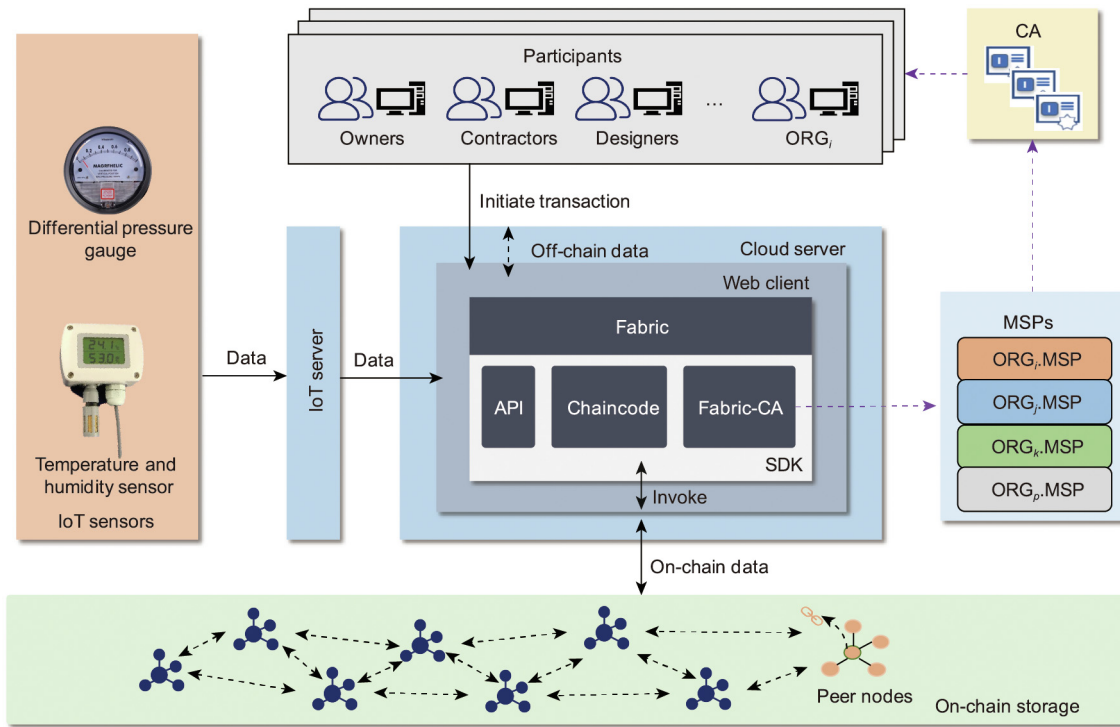


Fig. 2. System architecture of the blockchain-based hospital project life-cycle environmental management system. CA: certificate authority; MSP: membership service provider; API: application programming interface; ORG: organization; SDK: software development kit.

The privacy requirements and amount of data are the criteria for choosing either on-chain or off-chain storage. Off-chain data include large files and documents such as sensor data, design files, and forms. On-chain data mainly involve information related to the state of a process in the environmental management of infectious disease hospitals such as task-checking information, warning information, abnormal environmental state, and so forth.

We use design files and sensor data as examples to illustrate the off-chain information flow. This process is shown in Fig. 3. The creation and modification of the design file in different stages can reflect the progress of the project, and the blockchain can provide trust for the exchange of design files. The participant uploads the design file to the cloud through the web client, and the hash value of the design file is subsequently generated. The hash value of the design file, file name, timestamp, and digital signature are

uploaded to the blockchain network as immutable digital proof. When verifying the version of the file, the hash of the design file is calculated again to verify whether it is consistent with the hash value of the previous design file stored off-chain to determine whether the file has been modified. All sensor data are stored in the cloud, and the hash value is generated and stored on-chain. Simultaneously, some critical process data can be stored on-chain, given the traceability requirements in environmental monitoring.

3.2.3. Smart contract

A smart contract allows transactions to interface with the blockchain ledger. It serves as a conduit between project participants and blockchain ledgers. Below, we describe the functions of smart contracts and associated algorithms.

- Workflow coordination smart contract:** This smart contract facilitates the creation and execution of document approval. The main application scenarios of this smart contract in the project life cycle are design cooperation and compliance checking. Algorithms 1–3 describe the logic for recording the document's life cycles (creation, feedback, and revision). First, a document is created and uploaded to the off-chain layer, the hash value of the file is returned, the document uploader signs on the file, and the transaction TX_h is recorded on the blockchain network. Then, the document will be reviewed by another node. The reviewer can add feedback on the document, and the feedback transaction $TX_{h-feedback}$ is recorded on the blockchain ledger. Suppose that an operator wants to update an existing document. In that case, the smart contract will verify the digital signature on the original document with the operator's public key, and the document revision transaction $TX_{h-revision}$ will be recorded on the blockchain.

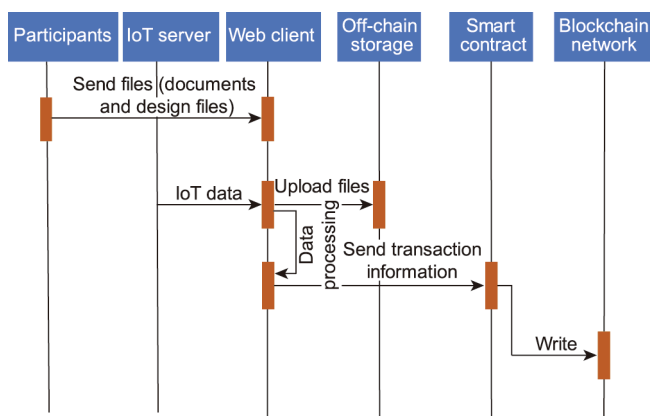


Fig. 3. Off-chain information flow in the proposed system architecture.

Algorithm 1. Generate a document for approval.**Input:** Document**Output:** Document transaction TX_h

1. **Foreach** Document do
2. Send Document to off-chain storage node;
3. Off-chain storage node returns HD = Hash(Document);
4. $Ts_h = \text{getTimeStamp}()$;
5. Generate signature of WorkflowInvoker Sig_h ;
6. Generate document creation transaction id IDD_h ;
7. Record HD, Ts_h , Sig_h , IDD_h in the transaction and generate TX_h ;
8. Return TX_h ;
9. **End**

Algorithm 2. Feedback on a document.**Input:** Document id IDD_h **Output:** Feedback transaction $TX_{h-feedback}$;

1. Search IDD_h and download the document from the off-chain storage node;
2. Add a comment on the document then generate a new file;
3. Send the new file to the off-chain storage node;
4. Off-chain storage node return HF = Hash (File);
5. Generate a timestamp Ts_h ;
6. Generate signature of reviewer $Sig_{h-reviewer}$;
7. Record HF, Ts_h , $Sig_{h-reviewer}$ in the transaction and generate $TX_{h-feedback}$;
8. Return $TX_{h-feedback}$;
9. **End**

Algorithm 3. Update an existing document.**Input:** Document id IDD_{h1} (old version), new_document (new version), signature on existing document Sig_h , operator's public key PK;**Output:** Document revision transaction $TX_{h-revision}$;

1. **If** $Sig_h = PK$ **then**
2. Send document2 to the off-chain storage node;
3. Link the old version's document id IDD_{h1} with the document id IDD_{h-new} in the document manager;
4. Record the old version's transaction detail and generate $TX_{h-revision}$;
5. Return $TX_{h-revision}$;
6. **Else**
7. Reject the transaction
8. **End**

- Automatic form-checking smart contract: Many forms (e.g., construction quality inspection forms and daily hospital maintenance record forms) can be predefined to support automatic work record checking in the project life cycle. Algorithm 4 shows the logic for automatic form checking. The value ranges for different items in the form are predefined in the smart contract. When an operator fills in the required values in the web interface and confirms the operation, the smart contract automatically checks the values in the form. If all values are within a predefined range, the form state is set to Pass. If there are

values in the form that are out of range, the form state is set to Fail, and warning information is sent to the person in charge. If the form state passes, TX_{h-form} is generated and uploaded to the blockchain network.

Algorithm 4. Automatic form checking.**Input:** Form, Lower_limit_value, Upper_limit_value**Output:** Form checking transaction TX_{h-form} ;

1. Search Lower_limit_value and Upper_limit_value for each Item in Form;
2. **If** all values are in value_range[Lower_limit_value, Upper_limit_value] **then**
3. Set Form_state as Pass;
4. Send Form to the off-chain storage node;
5. Off-chain storage node returns HF = Hash (Form);
6. $Ts_h = \text{getTimeStamp}()$;
7. Generate form creation transaction id IDF_h ;
8. Record HF, Ts_h , Form_state, IDF_h in the transaction and generate TX_{h-form} ;
9. Return TX_{h-form} ;
10. **Else**
11. Send warning information to the form creator node;
12. Set Form_state as Fail;
13. Send Form to the off-chain storage node;
14. Off-chain storage node returns HF = Hash(Form);
15. $Ts_h = \text{getTimeStamp}()$;
16. Generate form creation transaction id IDF_h ;
17. Record HF, Ts_h , Form_state, IDF_h in the transaction and generate TX_{h-form} ;
18. Return TX_{h-form} ;
19. **End**

- Environmental warning smart contract: In the operational stage, the indoor environmental parameters that affect biosafety are monitored by IoT sensors. Algorithm 5 was developed for monitoring the hospital environmental parameters in the operation stage. Each IoT sensor is assigned a unique ID, and the hash value of the sensor identity information is uploaded to the blockchain ledger, which ensures the reliability of the data source. The algorithm continuously judges whether the sensor value exceeds the acceptable range. Once the value of the device is out of range for a while, an alert is automatically sent to maintenance personnel, and the environmental warning transaction TX_{h-EW} is sent to related participants in the blockchain network.

Algorithm 5. IoT-based environmental warning.**Input:** sensor_ID, parameter_threshold_range, time_interval**Output:** Environmental warning transaction TX_{h-EW} ;

1. Search sensor_ID in IoT Server, get current_time, get sensor_value at current_time;
2. **If** current_sensor_value is not within environmental_threshold_range **then**
3. Get average_sensor_value in time_range[current_time, (current_time + time_interval)]
4. **If** average_sensor_value is not within parameter_threshold_range **then**
5. Send records in time_range[current_time, (current_time + time_interval)] to off-chain storage node;
6. Off-chain storage node returns HD = Hash(records);
7. $Ts_h = \text{getTimeStamp}()$;

(continued)

Algorithm 5. IoT-based environmental warning.

8. Generate warning_information including warning content, space_ID, sensor_ID, etc;
9. Generate environmental warning transaction TX_{h-EW} , including HD, Ts_h , warning_information, etc;
10. Send TX_{h-EW} to maintenance personnel;
11. Return TX_{h-EW} ;
12. **End**
13. **End**

4. Use cases

In this section, we develop use cases in the design, construction, and operation stages to illustrate how the blockchain-based framework can benefit healthcare facilities’ infection control while allowing them to meet fast delivery requirements in a pandemic situation. The user interfaces in these use cases are designed with Axure RP 9, a design tool for creating interactive HyperText markup language (HTML) prototypes for web applications. These use cases can be developed based on the proposed system architecture. These applications are related to the key infection control measures recommended in the guidelines published by the WHO, CDC, and ASHRAE for the design, construction, and operation of hospitals in the context of COVID-19.

We first introduce the use case in the design stage. During the COVID-19 pandemic, new hospitals were built, and some rooms in existing hospitals were retrofitted to create negative-pressure isolation wards for critically ill patients. Infection prevention guidelines published by the WHO and ASHRAE provide several key recommendations for reducing airborne infectious aerosol exposure in the design stage, including the layout design of different areas (polluted area, semi-polluted area, clean area, medical worker passage, and patient passage); the configuration of the negative-pressure ward; and the design of ventilation, filtration, and air cleaning [68,69]. The proposed blockchain-based solution

can transform how design collaboration and design approval occur and contribute to design liability control. It can ensure that the source of design errors that may affect the hospital’s environmental safety can be traced and that design files can be checked later if they cannot be checked on time in an urgent situation.

A typical scenario of a cycle of a design review process for a newly built healthcare facility or retrofitted healthcare unit in a normal situation is illustrated in Fig. 4. First, designers in different disciplines finish their design and submit the design files to the design team leader. The design team leader then checks the compliance with the design requirements. If the review items meet the requirements, the design documents are sent for approval. In a rapid delivery mode, there is not always enough time to complete a detailed design review and receive administrative approval, and designers must take more responsibility for their work quality. To meet the need for fast delivery, the framework developed in this study enables a different design review workflow based on a blockchain, which allows design files to be checked later so that the construction work can start earlier. The blockchain provides immutability and traceability for design files in order to realize design liability control. Due to the distributed storage characteristics of the blockchain, every upload and modification of the design file is recorded on the blockchain with a timestamp and the digital signature of the designers, so that the file cannot be tampered with. Fig. 5 shows that government regulators can approve the design first and review the design documents later or just review historical design files if problems occur in the construction or operation stage. The design team leader can also reduce the time required for a detailed design review. All design files are stored off-chain, and the hash values corresponding to the files are stored on the blockchain. With the unchangeable timestamp and digital signature in each transaction, the design approval process can be shortened while enhancing the designer’s sense of responsibility at the same time.

Fig. 6 shows a screenshot of the design collaboration interface in the prototype. All design participants can upload design files concerning the key infection control measures and related documents to the web client. The design files and some

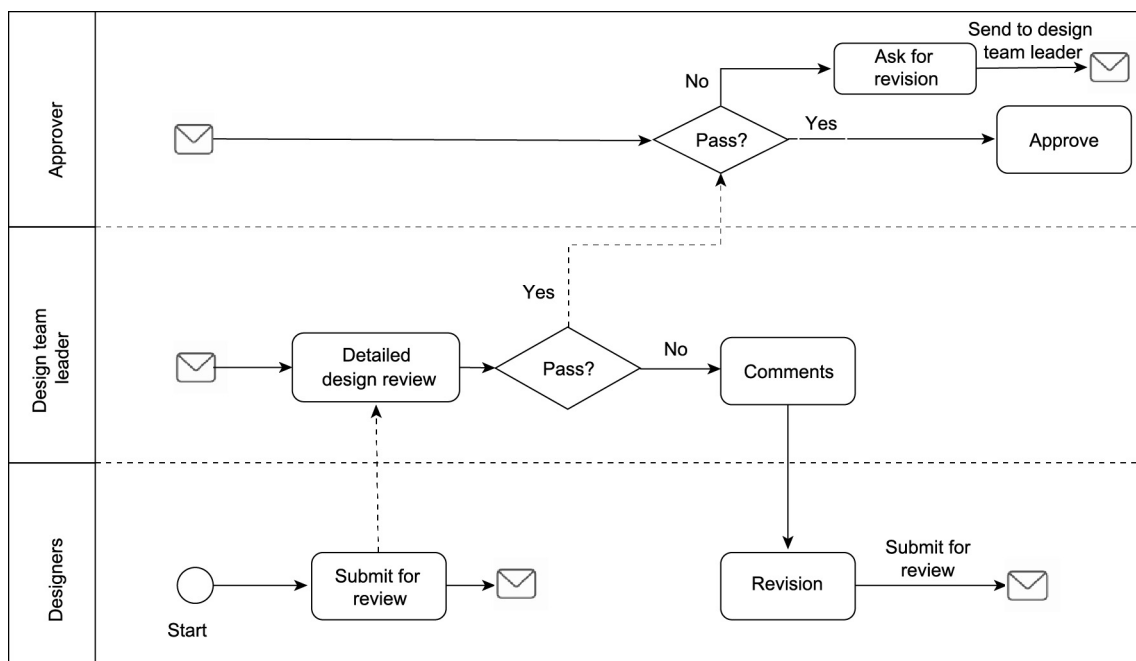


Fig. 4. Typical design review process for a newly built or retrofitted hospital in a normal situation.

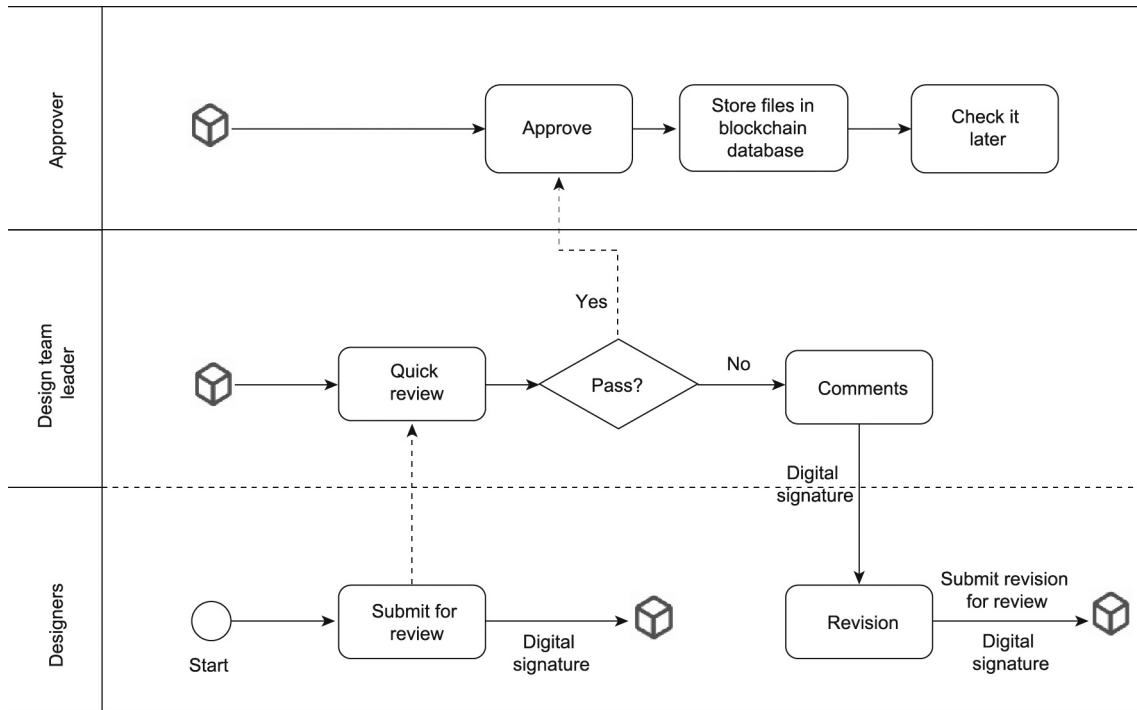


Fig. 5. New blockchain-enabled design review process under the fast delivery requirement.

Design Collaboration History
➔

Design File Layout design-v1

Timestamp 2020-9-19 09:13

Creator hospital staff@hospital2020.com

Design File Type Layout design

Linked File Design review comments.pdf

Transaction Hash [39f4545435feac9bd4d55c148f61d6eda34f95e0af4993c5e3c08adb16bf299d](#)

▶ **Design Files History**

Transaction Hash	Timestamp	Design File	Linked File	Creator	Transaction Status
c480a5194fe164..	2020-9-30 21:28	HVAC design-v2	HVAC design.pdf	MEP.designer@h..	Finish
dd0176aa920a96..	2020-9-23 09:59	HVAC design-v1	Design review comments.pdf	Reviewer@h..	Finish
2f26ba125febe6f..	2020-9-23 08:35	HVAC design-v1	HVAC design.pdf	MEP.designer@h..	Finish
39f4545435feac9..	2020-9-19 09:13	Layout design-v1	Design review comments.pdf	Reviewer@h..	Finish
e2ace6fdc5248e7..	2020-9-17 12:13	Layout design-v1	Layout design.pdf	architect.designe..	Finish

Fig. 6. Screenshot of the prototype (designed through Axure RP 9) for blockchain-based design collaboration.

unstructured files are stored in the cloud, whereas the hash value is stored on the blockchain. In the system, the digital signature, timestamp, file name, and file identity (hash) are recorded in the data exchange history to make the design process traceable. The history of design collaboration is permanently stored in the blockchain, and the record can be traced and cannot be tampered with. For example, if maintenance personnel detect a problem with the ventilation system in a

negative-pressure ward, they can easily search the heating, ventilation, and air conditioning (HVAC) design files and design review records in the blockchain storage with timestamps and the digital signature of the person in charge, which contributes to the accountability and traceability of environmental issues. The blockchain can record all design attempts and provide visible evidence of trust in the design process. The design files are stored in the off-chain layer. Moreover, design files are

encrypted into a hash, and the hash value is placed into on-chain storage. The hash value can be used to check the consistency of the file version.

Second, we illustrate how the proposed blockchain-based framework can transform the work mode of the construction inspection procedure during rapid delivery mode while ensuring the quality of delivery. In traditional construction inspection procedures (shown in Fig. 7), the next construction process can only be approved to start after the previous construction process has been checked. Similar to the transformation of the design review process, the construction process must be accelerated during a rapid delivery mode (shown in Fig. 8). With the proposed blockchain solution, the key construction process is immutably recorded on the blockchain and can be checked later so that the next construction procedure can start earlier.

According to the *Guidelines for environmental infection control in health-care facilities* [70], the construction quality of negative-

pressure wards is critical to the safe environment in healthcare facilities and must be monitored during the construction or renovation process. The construction quality of the negative-pressure ward is inextricably linked to the construction quality of the ventilation, filtration, and air cleaning system. After the construction of the negative-pressure isolation ward is completed, the construction quality of the negative-pressure ward must be checked, and indicators such as the pressure difference, room airflow direction, and air filtration efficiency must be strictly checked before they can be put into use. Fig. 9 shows that the construction quality record of the negative-pressure ward and other key items related to environmental safety of the hospital can be recorded to the blockchain with a timestamp and digital signature. The records can be checked by the owner or facility manager later, so that the engineers and workers can start the next construction process earlier. The immutable record will help improve the work quality in the construction process. The blockchain records facilitate the traceability of work liability during hospital operation. For example, if a quality problem occurs in the operation stage, the maintenance personnel can easily trace the construction quality record and ask for repair.

Third, we show how the proposed framework can help ensure a healthy and safe hospital environment for both patients and HCWs in the operation stage. As mentioned in the *Practical guidelines for infection control in health care facilities* published by the WHO [71], it is important to ensure that cleaning and disinfection procedures are followed consistently and correctly and that the devices of the ventilation, filtration, and air cleaning system are working properly.

First, as shown in Fig. 10, after completing the daily disinfection, cleaning, and inspection tasks for the ventilation, filtration, and air cleaning systems, the operator must upload the record to the blockchain for storage. The records can be checked by the facility manager in the future.

Then, the pressure difference of the negative-pressure ward is monitored in real time by the IoT sensor. Abnormal conditions are automatically uploaded to the blockchain as permanent records, and early warnings are sent to relevant network participants through the smart contract predefined in Fabric. Fig. 11

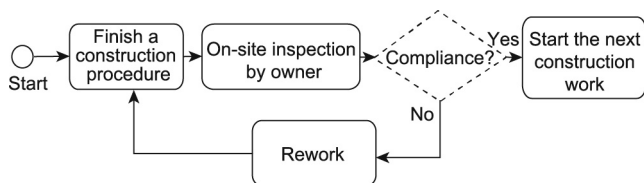


Fig. 7. Construction inspection procedure in a normal situation.

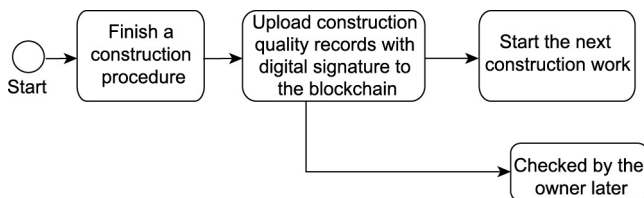


Fig. 8. Blockchain-enabled construction inspection procedure during a rapid construction mode.

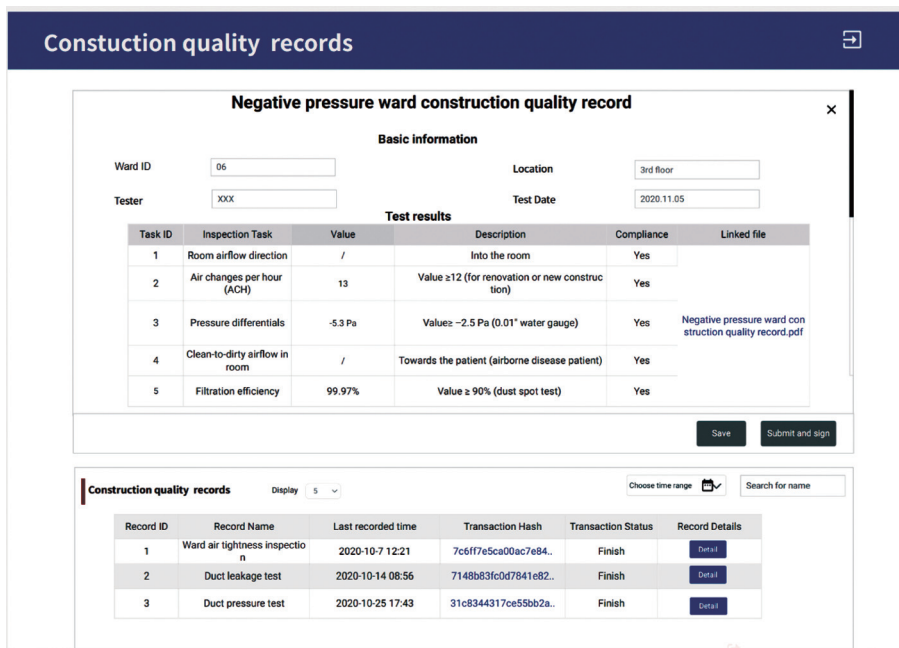


Fig. 9. User interface (designed through Axure RP 9) for process tracking in the construction stage.

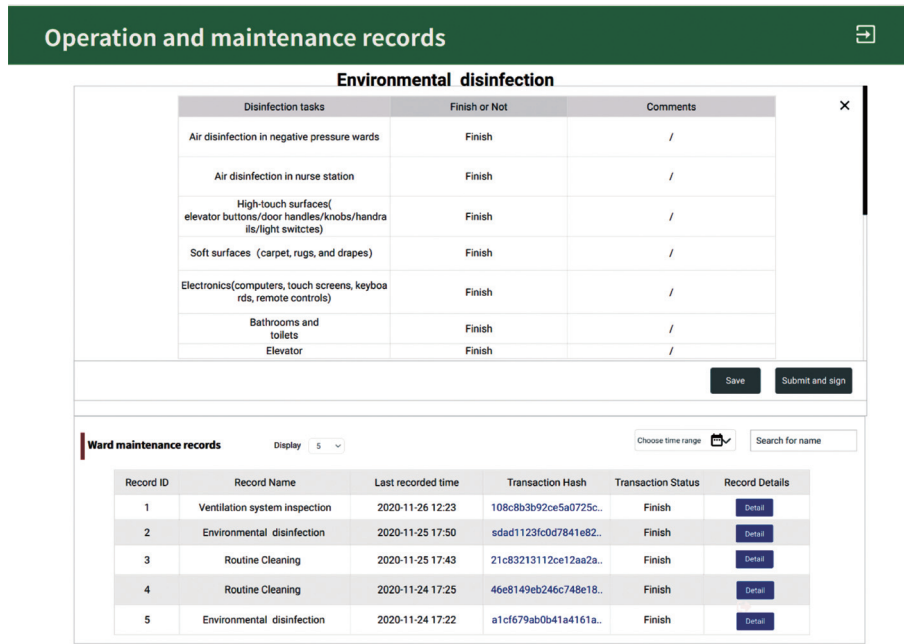


Fig. 10. User interface (designed through Axure RP 9) for daily environmental disinfection records tracking.

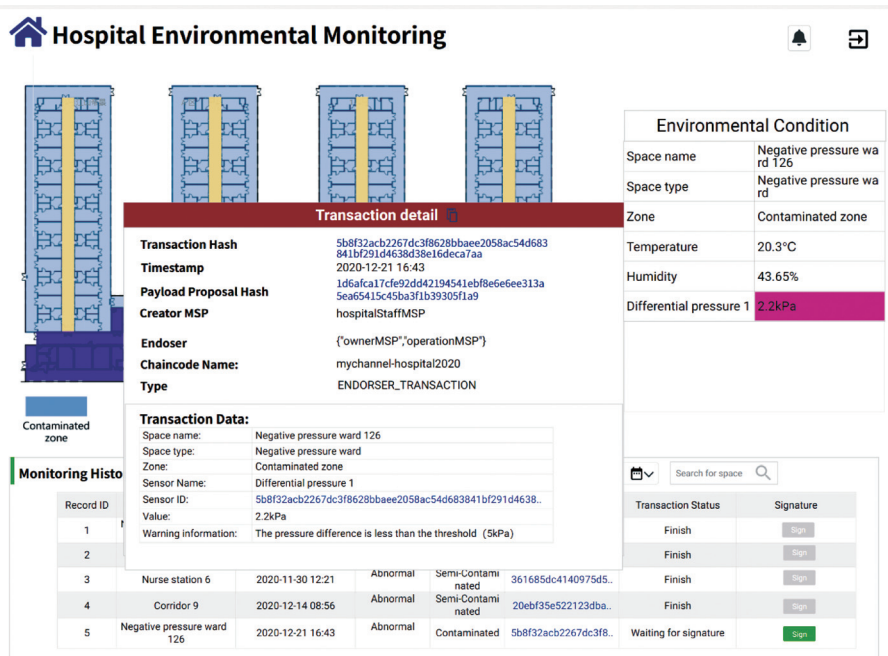


Fig. 11. Transaction detail of a hospital environmental monitoring record (designed through Axure RP 9).

shows the front page of the designed prototype for blockchain-based hospital environment monitoring. In Fig. 11, the pressure difference in a negative-pressure ward is lower than the standard value, and the record is automatically uploaded to the blockchain. Concerned participants can view the warning information in the transaction detail on the webpage. The transaction details include the transaction hash, timestamp, transaction status, space type, space ID, sensor ID, and other information. Moreover, the maintenance personnel can access the history state of the device. The maintenance staff must address the environmental

issue and then upload the maintenance record with a digital signature.

In summary, the selected use cases demonstrate that the proposed framework has the potential to help trace environmental issues and provide transparent and trustworthy documentation of process data related to nosocomial infection control measures through the life cycle of a hospital. It has the potential to change the way in which work inspection is done during a rapid delivery mode and to reduce the risk of hospital environment safety problems caused by a lack of thorough process inspections.

5. Evaluation

For the performance evaluation of the proposed system architecture, we first use the blockchain benchmark tool Hyperledger Caliper[†] to test the latency and throughput. Caliper can generate different transaction workloads by controlling the transaction sending rate. Then, the data storage is compared between the on-chain storage model and the off-chain storage model. The simulations are conducted on a computer with AMD Ryzen 7 4800U (1.80 GHz) and 16 GB RAM. The computer runs Ubuntu 20.04 LTS with Hyperledger Fabric (version 1.4.0) installed.

5.1. Latency

Transaction latency is the time that elapses between submitting a transaction and the result being widely available in the network. In the proposed scheme, records related to infection control measures should be recorded as transaction data on the blockchain. The project file sending transaction is considered to be the transaction with the highest frequency. The transaction send rate is a key factor for the blockchain performance test. We simulate the average transaction latency at different transaction send rates (i.e., 50, 100, 200, 500, and 1000 tps). The simulation results are shown in Fig. 12. The maximum transaction latency reaches 820 ms when the send rate reaches 500 tps, and the latency is less than 1 s. Unlike applications such as banking and online trading, the scenario in this study does not have a high requirement for latency, so the latency meets the requirement for the project.

5.2. Throughput

The transaction throughput is the rate at which valid transactions are committed by the blockchain in a certain time period. We test the average throughput of transactions at different transaction send rates. Fig. 13 shows that, when the send rate reaches 50 and 100 tps, the throughput reaches 48 and 99 tps, respectively. As the number of transactions increases after 200 tps, the throughput becomes stable near 140 tps. For a consortium blockchain application, there are a limited number of participants in the network; thus, the throughput meets the operational requirement of the system.

5.3. Storage analysis

To compare the storage cost of the off-chain storage and on-chain storage, we set the block header to the standard 80 B and the block size to 1 MB. Take the storage of the work process record form as an example. Let us assume that the average data size of the work checking form is 20 KB. For the off-chain storage scheme, the maximum data size of a transaction is 300 B in the proposed applications. The capacity of a block is 1 MB. Thus, 100 blocks can hold 5 120 transactions in an on-chain storage scheme and 349 525 transactions in an off-chain storage scheme. A single block can hold a greater number of transactions in an off-chain storage scheme than in an on-chain storage scheme. To store 1 000 transactions, the off-chain storage scheme requires 300 000 B, whereas the on-chain storage scheme needs 20 480 000 B. Therefore, the off-chain storage model saves more storage space and achieves higher throughput. The off-chain storage model enables every node to download the full transaction history of the block, instead of only the block header.

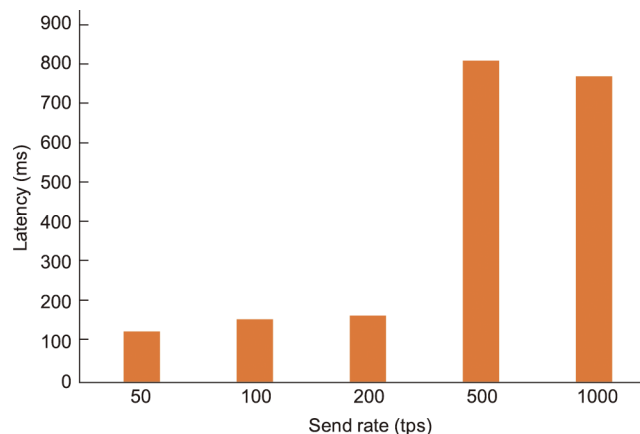


Fig. 12. Average transaction latency at different send rates.

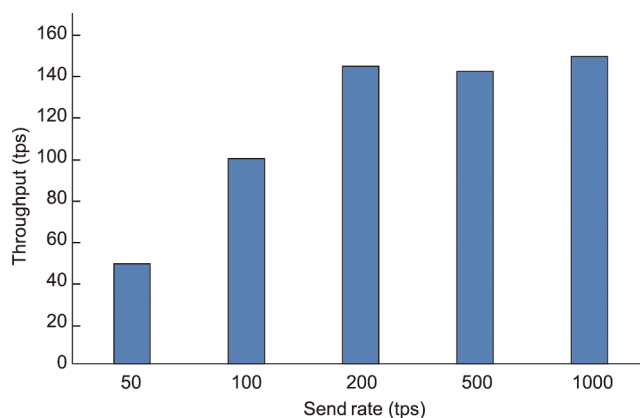


Fig. 13. Average transaction throughput at different send rates.

6. Discussion

This study explores how blockchain technology can assist in the environmental management of COVID-19 healthcare facilities during a rapid delivery mode. The main theoretical implications are as follows. First, compared with previous literature on the application of blockchain technology for coping with the COVID-19 pandemic, this study provides a new blockchain application for nosocomial infection control in healthcare facilities. Second, this study provides an example of how blockchains can help to address challenges in emergency engineering management. Third, the previous studies focusing on nosocomial infection control are usually limited to a specific aspect, such as ventilation, disinfection, or PPE wearing. Unlike the previous literature, this study addresses environmental management problems from the perspective of the project life cycle and provides traceability for key infection control measures in different aspects throughout the design, construction, and operation stages.

From the managerial perspective, the environmental management of COVID-19 healthcare facilities is crucial in containing the spread of pathogens and protecting the health and safety of people. During the rapid delivery of a new hospital or hospital renovations, there may be a lack of work quality control, which could lead to issues with the hospital environment. In a COVID-19 emergency, the proposed framework can ensure an immutable record of events and guarantee the authenticity of records. This enables work that cannot be checked on time to be checked later. It provides a

[†] <https://github.com/hyperledger/caliper>.

potential solution for the contradiction between speed and work quality during a rapid delivery mode by providing data traceability and accountability for the fulfillment of key infection control measures in the design, construction, and operation of COVID-19 healthcare facilities.

The proposed work provides a possible option for establishing a consortium blockchain for healthcare facilities in multiple regions. When there is a surge in infection cases in a certain area and hospitals must be built or renovated, the proposed blockchain solution can help with environmental management in the project life cycle in order to reduce the risk of nosocomial infection.

7. Conclusions

At present, the COVID-19 pandemic has rapidly progressed worldwide. To ensure biosafety in hospitals during a rapid delivery mode, a life-cycle environmental management framework is proposed in this study. A consortium blockchain is developed to record process data into a distributed ledger in order to support accountability and traceability of the fulfillment of key infection control measures. The need for the rapid delivery of infectious disease hospitals during certain urgent situations introduces difficulties into work quality assurance. The main contributions of this study are as follows: ① This study provides new insights into the research area of using blockchain applications to cope with the COVID-19 pandemic. A blockchain-based framework is developed to deal with nosocomial infection control in the environmental management of healthcare facilities. ② The proposed blockchain-based framework holds potential to benefit work quality inspection practice during a rapid delivery mode. It can provide immutability for work records so that some work can be checked later in urgent situations. The conceptual framework, system architecture, and use cases are developed from the perspective of the hospital life cycle and can provide guidance to practitioners in developing blockchain solutions for work process tracking during the design, construction, and operation of hospitals.

The investigation of blockchain-based hospital environmental management is still in a preliminary stage. The configuration of the blockchain network in practice must consider different organizations, participants, and privacy protection requirements. Standardization and modularity must be considered in practice, which can help reduce costs and improve deployment efficiency. This study only considers the role of blockchain technology in emergency engineering projects from the perspective of work quality management. Future work will explore how blockchains can facilitate collaboration among various parties in emergency projects and will study the responsibility-sharing mechanism among project participants in blockchain-based work environments.

Acknowledgments

This research is partly supported by the National Natural Science Foundation of China (71732001, 51878311, 72271106, U21A20151, and 71821001), Engineering Fronts Project (2021-HYZD-5-13), Major Science & Technology Project of Hubei (2020ACA006), and China Scholarship Council (202006160115). The authors thank Professor Timo Hartmann (Technical University of Berlin) for his advice on this paper.

Compliance with ethics guidelines

Botao Zhong, Han Gao, Lieyun Ding, and Yuhang Wang declare that they have no conflict of interest or financial conflicts to disclose.

References

- [1] Wang D, Hu B, Hu C, Zhu F, Liu X, Zhang J, et al. Clinical characteristics of 138 hospitalized patients with 2019 novel coronavirus-infected pneumonia in Wuhan, China. *JAMA* 2020;323(11):1061–9.
- [2] Jones TC, Biele G, Mühlemann B, Veith T, Schneider J, Beheim-Schwarzbach J, et al. Estimating infectiousness throughout SARS-CoV-2 infection course. *Science* 2021;373(6551):180–93.
- [3] PAHO. COVID-19 has infected some 570 000 health workers and killed 2 500 in the Americas. PAHO Director says [Internet]. Washington, DC: PAHO; 2020 Sep 2 [cited 2022 Feb 2]. Available from: <https://www.paho.org/en/news/2-9-2020-covid-19-has-infected-some-570000-health-workers-and-killed-2500-americas-paho>.
- [4] Alshamrani MM, El-Saed A, Al Zunitan M, Almulhem R, Almohrij S. Risk of COVID-19 morbidity and mortality among healthcare workers working in a large tertiary care hospital. *Int J Infect Dis* 2021;109:238–43.
- [5] Read JM, Green CA, Harrison EM, Docherty AB, Funk S, Harrison J, et al.; ISARIC4C investigators. Hospital-acquired SARS-CoV-2 infection in the UK's first COVID-19 pandemic wave. *Lancet* 2021;398(10305):1037–8.
- [6] Liu Z, Wang L, Rong R, Fu S, Cao G, Hao C. Full-scale experimental and numerical study of bioaerosol characteristics against cross-infection in a two-bed hospital ward. *Build Environ* 2020;186:107373.
- [7] Ge T, Lu Y, Zheng S, Zhuo L, Yu L, Ni Z, et al. Evaluation of disinfection procedures in a designated hospital for COVID-19. *Am J Infect Control* 2021;49(4):447–51.
- [8] Kampf G, Todt D, Pfaender S, Steinmann E. Persistence of coronaviruses on inanimate surfaces and their inactivation with biocidal agents. *J Hosp Infect* 2020;104(3):246–51.
- [9] Liow MHL, Lee LC, Tan NCK, Tan HK, Chow W, Wee GLE, et al. Personal protective equipment training for non-healthcare workers in the COVID-19 pandemic: effectiveness of an evidence-based skills training framework. *Infect Dis Heal* 2021;27(1):38–48.
- [10] Ren J, Wang Y, Liu Q, Liu Y. Numerical study of three ventilation strategies in a prefabricated COVID-19 inpatient ward. *Build Environ* 2021;188:107467.
- [11] Srivastava S, Zhao X, Manay A, Chen Q. Effective ventilation and air disinfection system for reducing coronavirus disease 2019 (COVID-19) infection risk in office buildings. *Sustain Cities Soc* 2021;75:103408.
- [12] Miller SL, Clements N, Elliott SA, Subhash SS, Eagan A, Radonovich LJ. Implementing a negative-pressure isolation ward for a surge in airborne infectious patients. *Am J Infect Control* 2017;45(6):652–9.
- [13] Ereth MH, Fine J, Stamatatos F, Mathew B, Hess D, Simpson E. Healthcare-associated infection impact with bioaerosol treatment and COVID-19 mitigation measures. *J Hosp Infect* 2021;116:69–77.
- [14] Walker JT, Hoffman P, Bennett AM, Vos MC, Thomas M, Tomlinson N. Hospital and community acquired infection and the built environment—design and testing of infection control rooms. *J Hosp Infect* 2007;65(Suppl 2):S43–9.
- [15] Ataullah AHM, Rahman S, Ridoy MNH, Turaeva N, Lozada-Martinez ID, Moscote-Salazar LR, et al. Impact on surgical wards in COVID-19 pandemic & safe surgery. *Int J Surg Open* 2021;30:100320.
- [16] Yang M, Wang H, Li Z, Zhang Q, Liu X, He M, et al. Prevention and control of COVID-19 infection in a Chinese mental health center. *Front Med* 2020;7:356.
- [17] Zhou J, Otter JA, Price JR, Cimpeanu C, Garcia DM, Kinross J, et al. Investigating SARS-CoV-2 surface and air contamination in an acute healthcare setting during the peak of the COVID-19 pandemic in London. *Clin Infect Dis* 2020;73(7):e1870–7.
- [18] Menon S, Jain K. Blockchain technology for transparency in agri-food supply chain: use cases, limitations, and future directions. *IEEE Trans Eng Manage* 2021;99:1–15.
- [19] Guggenberger T, Schweizer A, Urbach N. Improving interorganizational information sharing for vendor managed inventory: toward a decentralized information hub using blockchain technology. *IEEE Trans Eng Manage* 2020;67(4):1074–85.
- [20] Du M, Chen Q, Chen J, Ma X. An optimized consortium blockchain for medical information sharing. *IEEE Trans Eng Manage* 2020;68(6):1677–89.
- [21] Biswas S, Sharif K, Li F, Latif Z, Kanhere SS, Mohanty SP. Interoperability and synchronization management of blockchain-based decentralized e-health systems. *IEEE Trans Eng Manage* 2020;67(4):1363–76.
- [22] Aslam B, Javed AR, Chakraborty C, Nebhen J, Raqib S, Rizwan M. Blockchain and ANFIS empowered IoMT application for privacy preserved contact tracing in COVID-19 pandemic. *Pers Ubiquitous Comput* 2021 Jul:1–17.
- [23] Song J, Gu T, Feng X, Ge Y, Mohapatra P. Blockchain meets COVID-19: a framework for contact information sharing and risk notification system 2020. arXiv:200710529.
- [24] Manoj M, Srivastava G, Somayaji SRK, Gadekallu TR, Maddikunta PKR, Bhattacharya S. An incentive based approach for COVID-19 planning using blockchain technology. In: *Proceedings of the 2020 IEEE Globecom Workshops (GC Wkshps)*; 2020 Dec 7–11; Taipei, China. Piscataway: IEEE; 2020.
- [25] Ouyang L, Yuan Y, Cao Y, Wang FY. A novel framework of collaborative early warning for COVID-19 based on blockchain and smart contracts. *Inf Sci* 2021;570:124–43.
- [26] Lee HA, Kung HH, Lee YJ, Chao JCJ, Udayasankaran JG, Fan HC, et al. Global infectious disease surveillance and case tracking system for COVID-19: development study. *JMIR Med Inform* 2020;8(12):e20567.

- [27] Gupta R, Kumari A, Tanwar S, Kumar N. Blockchain-envisioned softwarized multi-swarming uavs to tackle COVID-19 situations. *IEEE Netw* 2021;35(2):160–7.
- [28] Shamsi K, Khorasani KE, Shayegan MJ. A secure and efficient approach for issuing KYC token as COVID-19 health certificate based on stellar blockchain network. 2020. arXiv:201002169.
- [29] Yu K, Tan L, Shang X, Huang J, Srivastava G, Chatterjee P. Efficient and privacy-preserving medical research support platform against COVID-19: a blockchain-based approach. *IEEE Consum Electron Mag* 2021;10(2):111–20.
- [30] Antal C, Cioara T, Antal M, Anghel I. Blockchain platform for COVID-19 vaccine supply management. *IEEE Open J Comput Soc* 2021;2:164–78.
- [31] Nakamoto S. Bitcoin: a peer-to-peer electronic cash system [Internet]. 2008 [cited 2022 Feb 26]. Available from: <https://bitcoin.org/bitcoin.pdf>.
- [32] Miglani A, Kumar N, Chamola V, Zeadally S. Blockchain for internet of energy management: review, solutions, and challenges. *Comput Commun* 2020;151:395–418.
- [33] Hammi MT, Hammi B, Bellot P, Serhrouchni A. Bubbles of trust: a decentralized blockchain-based authentication system for IoT. *Comput Secur* 2018;78:126–42.
- [34] Eisenstadt M, Ramachandran M, Chowdhury N, Third A, Domingue J. COVID-19 antibody test/vaccination certification: there's an app for that. *IEEE Open J Eng Med Biol* 2020;1:148–55.
- [35] Ahmad RW, Salah K, Jayaraman R, Yaqoob I, Omar M, Ellahham S. Blockchain-based forward supply chain and waste management for COVID-19 medical equipment and supplies. *IEEE Access* 2021;9:44905–27.
- [36] Sathya AR, Banik BG. An approach of trustworthy supply chain management of ventilator and PPE in COVID-19 pandemic through blockchain technology. In: Tavares JMRS, Dutta P, Dutta S, Samanta D, editors. *Cyber intelligence and information retrieval*. Berlin: Springer; 2022. p. 445–53.
- [37] Christodoulou K, Christodoulou P, Zinonos Z, Carayannis EG, Chatzichristofis SA. Health information exchange with blockchain amid COVID-19-like pandemics. In: *Proceedings of the 2020 16th International Conference on Distributed Computing in Sensor Systems (DCOSS)*; 2020 May 25–27; Marina del Rey, CA, USA. Piscataway: IEEE; 2020. p. 412–7.
- [38] Kumar R, Tripathi R. A secure and distributed framework for sharing COVID-19 patient reports using consortium blockchain and IPFS. In: *Proceedings of the 2020 Sixth International Conference on Parallel, Distributed and Grid Computing (PDGC)*; 2020 Nov 6–8; Wanknaghat, India. Piscataway: IEEE; 2020. p. 231–6.
- [39] Gordon DE, Jang GM, Bouhaddou M, Xu J, Obernier K, White KM, et al. A SARS-CoV-2 protein interaction map reveals targets for drug repurposing. *Nature* 2020;583(7816):459–68.
- [40] Kovács G, Falagari SI. Lessons learned from humanitarian logistics to manage supply chain disruptions. *J Supply Chain Manag* 2021;57(1):41–9.
- [41] Khurshid A. Applying blockchain technology to address the crisis of trust during the COVID-19 pandemic. *JMIR Med Inform* 2020;8(9):e20477.
- [42] Ho D. Addressing COVID-19 drug development with artificial intelligence. *Adv Intell Syst* 2020;2(5):2000070.
- [43] Alexander GC, Qato DM. Ensuring access to medications in the US during the COVID-19 pandemic. *JAMA* 2020;324(1):31–2.
- [44] Bandara E, Liang X, Foytik P, Shetty S, Hall C, Bowden D, et al. A blockchain empowered and privacy preserving digital contact tracing platform. *Inf Process Manage* 2021;58(4):102572.
- [45] Wang J, Wu P, Wang X, Shou W. The outlook of blockchain technology for construction engineering management. *Front Eng Manag* 2017;4(1):67–75.
- [46] Turk Ž, Klinc R. Potentials of blockchain technology for construction management. *Procedia Eng* 2017;196:638–45.
- [47] Li J, Greenwood D, Kassem M. Blockchain in the built environment and construction industry: a systematic review, conceptual models and practical use cases. *Autom Construct* 2019;102:288–307.
- [48] Pradeep ASE, Yiu TW, Zou Y, Amor R. Blockchain-aided information exchange records for design liability control and improved security. *Autom Construct* 2021;126:103667.
- [49] Sheng D, Ding L, Zhong B, Love PED, Luo H, Chen J. Construction quality information management with blockchains. *Autom Construct* 2020;120:103373.
- [50] Lu W, Wu L, Zhao R, Li X, Xue F. Blockchain technology for governmental supervision of construction work: learning from digital currency electronic payment systems. *J Constr Eng Manag* 2021;147(10):04021122.
- [51] Hamledari H, Fischer M. Measuring the impact of blockchain and smart contracts on construction supply chain visibility. *Adv Eng Inform* 2021;50:101444.
- [52] Wang Z, Wang T, Hu H, Gong J, Ren X, Xiao Q. Blockchain-based framework for improving supply chain traceability and information sharing in precast construction. *Autom Construct* 2020;111:103063.
- [53] Elghaish F, Abrishami S, Hosseini MR. Integrated project delivery with blockchain: an automated financial system. *Autom Construct* 2020;114:103182.
- [54] Pollack J, Helm J, Adler D. What is the Iron Triangle, and how has it changed? *Int J Manag Proj Bus* 2018;11(2):527–47.
- [55] Mungmuntipantip R, Wiwanitkit V. Building Pathology and COVID-19: a literature review and commentary on field hospital setting. *Int J Real Estate Stud* 2021;15(1):112–6.
- [56] Lu H, Wang H, Yu D, Ye J. Sharp schedule compression in urgent emergency construction projects via activity crashing, substitution and overlapping: a case study of Huoshengshan and Leishenshan hospital projects in Wuhan. *Eng Constr Archit Manag*. In press.
- [57] Zheng R, Jiang J, Hao X, Ren W, Xiong F, Ren Y. BcBIM: a blockchain-based big data model for BIM modification audit and provenance in mobile cloud. *Math Probl Eng* 2019;2019:5349538.
- [58] Helliari CV, Crawford L, Rocca L, Teodori C, Veneziani M. Permissionless and permissioned blockchain diffusion. *Int J Inf Manage* 2020;54:102136.
- [59] Leng J, Ruan G, Jiang P, Xu K, Liu Q, Zhou X, et al. Blockchain-empowered sustainable manufacturing and product lifecycle management in industry 4.0: a survey. *Renew Sustain Energy Rev* 2020;132:110112.
- [60] Hattori T, Ishida R. Did the introduction of Bitcoin futures crash the Bitcoin market at the end of 2017? *North Am J Econ Financ* 2020;56:101322.
- [61] Farrugia S, Ellul J, Azzopardi G. Detection of illicit accounts over the Ethereum blockchain. *Expert Syst Appl* 2020;150:113318.
- [62] Salimitari M, Chatterjee M, Fallah YP. A survey on consensus methods in blockchain for resource-constrained IoT networks. *Internet Things* 2020;11:100212.
- [63] Kotilevets ID, Ivanova IA, Romanov IO, Magomedov SG, Nikonov VV, Pavelev SA. Implementation of directed acyclic graph in blockchain network to improve security and speed of transactions. *IFAC-PapersOnLine* 2018;51(30):693–6.
- [64] Shi S, He D, Li L, Kumar N, Khan MK, Choo KR. Applications of blockchain in ensuring the security and privacy of electronic health record systems: a survey. *Comput Secur* 2020;97:101966.
- [65] Fan K, Sun S, Yan Z, Pan Q, Li H, Yang Y. A blockchain-based clock synchronization scheme in IoT. *Future Gener Comput Syst* 2019;101:524–33.
- [66] Perera S, Nanayakkara S, Rodrigo MNN, Senaratne S, Weinand R. Blockchain technology: is it hype or real in the construction industry? *J Ind Inf Integr* 2020;17:100125.
- [67] Zhang S, Rong J, Wang B. A privacy protection scheme of smart meter for decentralized smart home environment based on consortium blockchain. *Electr Power Energy Syst* 2020;121:106140.
- [68] World Health Organization. Annex to infection prevention and control during health care when coronavirus disease (COVID-19) is suspected or confirmed [Internet]. Geneva: World Health Organization; 2021 Oct 1 [cited 2022 Feb 26]. Available from: <https://www.who.int/publications/i/item/WHO-2019-nCoV-IPC-Annex-2021.1>.
- [69] Bahnfleth W, Degraw J. Reducing airborne infectious aerosol exposure. *ASHRAE J* 2021;63(5):18–21.
- [70] Sehulster LM, Chinn RYW, Arduino MJ, Carpenter J, Donlan R, Ashford D, et al. Guidelines for environmental infection control in health-care facilities; recommendations of CDC and Healthcare Infection Control Practices Advisory Committee (HICPAC). Chicago, IL: American Society for Healthcare Engineering/American Hospital Association; 2004.
- [71] World Health Organization. Practical guidelines for infection control in health care facilities [Internet]. Geneva: World Health Organization; 2005 Aug 4 [cited 2022 Feb 26]. Available from: <https://www.who.int/publications/i/item/practical-guidelines-for-infection-control-in-health-care-facilities>.