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Blockchain-based digital twin data provenance for predictive asset management in building facilities

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Abstract

Purpose – The purpose of this study is to focus on structured data provision and asset information model maintenance and develop a data provenance model on a blockchain-based digital twin smart and sustainable built environment (DT) for predictive asset management (PAM) in building facilities.

Design/methodology/approach – Qualitative research data were collected through a comprehensive scoping review of secondary sources. Additionally, primary data were gathered through interviews with industry specialists. The analysis of the data served as the basis for developing blockchain-based DT data provenance models and scenarios. A case study involving a conference room in an office building in Stockholm was conducted to assess the proposed data provenance model. The implementation utilized the Remix Ethereum platform and Sepolia testnet.

Findings – Based on the analysis of results, a data provenance model on blockchain-based DT which ensures the reliability and trustworthiness of data used in PAM processes was developed. This was achieved by providing a transparent and immutable record of data origin, ownership and lineage.

Practical implications – The proposed model enables decentralized applications (DApps) to publish real-time data obtained from dynamic operations and maintenance processes, enhancing the reliability and effectiveness of data for PAM.

Originality/value – The research presents a data provenance model on a blockchain-based DT, specifically tailored to PAM in building facilities. The proposed model enhances decision-making processes related to PAM by ensuring data reliability and trustworthiness and providing valuable insights for specialists and stakeholders interested in the application of blockchain technology in asset management and data provenance.

Keywords Asset information requirements, Asset information model, Digital twins, Blockchain, Data provenance, Predictive asset management

Paper type Research paper

1. Introduction

Building facilities are critical assets that require effective management to ensure their optimal performance. Predictive asset management (PAM) is a key strategy for ensuring efficient and cost-effective building facility maintenance, repair and replacement (Bouabdallaoui *et al.*, 2021; Hellenborn *et al.*, 2023; Petrović *et al.*, 2022). With the advent of digital technologies, there is an increasing demand for digital twin (DT), virtual replicas of physical assets, to support PAM. However, the collection and management of data for DT pose significant

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challenges, including data provenance, data quality and data security (Hellenborn *et al.*, 2023; Lee *et al.*, 2021). Data provenance refers to the complete history of a piece of data, including its creation, handling and storage. In the context of building facilities, DT technology can provide a virtual replica of a physical asset, allowing for real-time monitoring and analysis of its condition and performance (Liang *et al.*, 2017; Zheng *et al.*, 2019).

However, providing a suitable database for storing and using this provenance data is essential. Blockchain technology (BCT) can be used to implement a decentralized, secure and transparent database that can store data immutably and provide a tamper-proof record of transactions. By using BCT, it is possible to establish a secure and transparent data provenance system for DT data, thereby improving quality, reliability and traceability of data. By combining DT technology with blockchain-based data provenance, building facilities can benefit from a secure and transparent system for PAM (Liang *et al.*, 2017; Zheng *et al.*, 2019; Casino *et al.*, 2019; Hastig and Sodhi, 2020; Jabbar *et al.*, 2021; Kuperberg and Geipel, 2021). Smart contracts and decentralized applications (DApps) also play a critical role in this process by automating decision-making and ensuring that all data transactions are secure and tamper-proof (Casino *et al.*, 2019; Putz *et al.*, 2021; Shakila and Sultana, 2021). This automation and decision-making along with safeness provide a robust and flexible framework for PAM, ensuring that the building facility is operated and maintained optimally (Bouabdallaoui *et al.*, 2021; Hellenborn *et al.*, 2023).

There is a knowledge gap and challenges in building facility management (FM) when it comes to using BCT for managing and processing data provenance. The debate around predicting and preventing building asset issues, like components, has been presented. Traditional monitoring tools have been used, but they are not sufficient to monitor, prevent and predict the status of assets in the building. FM companies realized the requirement to go digital and utilize Internet of thing (IoT) and sensors is to define data and information in a digital format (Sepasgozar *et al.*, 2023).

To address these challenges, a data provenance model on blockchain-based DT is proposed. The objective of this study is to develop a model that uses BCT to support data provenance for PAM in building facilities. The DApps front end will be able to make available real-time information such as monitoring conditions, fault detection and maintenance planning (Sadri *et al.*, 2023). This information has been collected from the dynamic operation and maintenance (O&M) data in this research case study. Thereby, three research questions are posed for reaching this objective:

RQ1. What are the dynamic data structures required in blockchain platform for the purposes of monitoring conditions, fault detection, and maintenance planning?

RQ2. How is the data provenance organized in managing meta-data, conducting data audits, demanding data traceability and visualization of data in the Model?

RQ3. How can the proposed data provenance model on blockchain-based DT support PAM in terms of data quality, data security and data transparency in building facilities?

In the next section, theoretical background is addressed and then the methodology including a qualitative study (semi-structured interviews) and a case study involving a conference room in the office building at Stockholm are presented. The analysis of results is presented in section 4 followed by the discussion in section 5. Finally, the conclusion is provided along with recommendations for future research.

2. Theoretical background

2.1 Blockchain in predictive asset management

Bouabdallaoui *et al.* (2021) proposed a predictive maintenance framework for heating ventilation and air conditioning installations using IoT and a building automation system as machine learning techniques. Five processes that make up the predictive maintenance framework are (1) data gathering, (2) data processing, (3) model construction, (4) defect notification and (5) model refinement. The study discovered that the framework had the ability to foresee failures, but it also encountered challenges with data accessibility and feedback gathering with a sports facility as a case study. Predictive maintenance is a proactive approach used in building management to anticipate and prevent potential equipment issues before they lead to costly breakdowns. It involves leveraging data and technology to foresee problems, ensuring that repairs are made at the most opportune times. This strategy not only saves on unexpected repair costs but also helps maintain the smooth operation of building systems. However, it does come with its share of challenges, such as obtaining accurate data, especially for older systems, and the initial investment required for advanced data collection and analysis tools. Balancing the benefits with these complexities is crucial when considering predictive maintenance implementation. Götz *et al.* (2020) developed a framework for situating the DT inside current management practices and technology capabilities. The framework also investigated the applicability, interoperability and integrability of a blockchain-based DT for asset life cycle management. Integrability enablers include BIM level 3, which represents the implementation and involves utilizing asset information models (AIM) for effective life cycle asset management. It also emphasizes the integration of services to promote collaboration among project stakeholders (Bew and Richards, 2008), decentralized program hubs and modular interfaces. Nonetheless, the study recognizes constraints such as the early stage of technology adaption and a lack of economics, implementation strategies and competency requirements for facility managers (Götz *et al.*, 2020; Stojanovic *et al.*, 2022).

Hellenborn *et al.* (2023) identified the key data categories and characteristics defined by asset information requirements (AIR) and their effect on the development and maintenance of an AIM for a blockchain-based DT. Three key data categories were identified: core data, static operation and maintenance data, and dynamic operation and maintenance data. The findings highlighted the importance of an ontology-based data structure for AIM to support predictive data-driven analytics through AI in a blockchain-based DT. BCT has the potential to provide additional reliability, authenticity and transparency to DT, but its utilization depends on multiple factors, including technical limitations.

BCT has the potential to enhance data reliability and transparency in PAM for O&M in FM (Shakila and Sultana, 2021). However, the issue of data provenance in BCT can pose challenges in accurately tracking data origin and history. To address this, an AIR and AIM that utilize an ontology-based data structure are essential to support predictive data-driven analytics through AI in a blockchain-based DT for effective predictive maintenance during the O&M phase (Hellenborn *et al.*, 2023).

2.2 Blockchain-based digital twins

Putz *et al.* (2021) developed the EtherTwin DApp, which is a decentralized application that implements a secure and decentralized data sharing model for DT in the industry 4.0 landscape. The solution relies on blockchain-based access control and encrypted off-chain data storage to ensure availability, integrity and confidentiality of DT data. The implementation uses Ethereum blockchain and Swarm as a decentralized storage and has been validated through use case elaboration and performance testing, as well as expert interviews. The solution is open source and has potential for further research and development in areas such as health DT data sharing, data marketplaces and machine certifications. The prototype could also be enhanced to allow for data flow from the DT to the physical asset, and the integration of simulation environments into the decentralized sharing platform.

The use of blockchain-based DT in industrial processes can provide trustworthy data and improve efficiency. Suhail *et al.* (2021) mention to ensure the reliability of physical data, it is essential to validate it by comparing information from different sensors that have overlapping areas of observation. Cross-validated sensory data can be recorded on the BCT to maintain its integrity and trustworthiness. DT can use this data to identify faults and make predictions for improved process monitoring and control. Integrating BCT in DT helps stakeholders manage data securely on a shared ledger, while integrating AI provides intelligent twins for predictive maintenance and threat intelligence. A trustworthy 7D blockchain-based DT framework (which present the data synchronization between virtual space and physical space with blockchain; integration and interoperability of components such as data fusion, data wrangler and composability) has been proposed based on the identified research gaps. However, further investigation is needed for the successful implementation of blockchain-based DT (Suhail *et al.*, 2021, 2022). DT are simulations of real-world physical components that play a vital role in Industry 4.0. BCT can enhance DT by/ providing secure manufacturing, traceability, compliance, authenticity and safety. Yaqoob *et al.* (2020) presented taxonomy of DT literature and recent case studies. The main challenges are scalability, standardization, regulations, data privacy and interoperability as barriers to successful adoption of BCT in DT. DT infrastructure needs to be aligned with smart IoT-enabled devices, cognitive behavior should be incorporated using machine learning, and larger enterprises, manufacturers and government agencies should come together to develop new policies.

2.3 Provenance knowledge in blockchain

Zheng *et al.* (2019) demonstrate that the bcBIM is a novel building information modeling (BIM) system that aims to enhance information security in the architecture, engineering and construction industries. It uses BCT and enables BIM data provenance audit for historical modifications and big data sharing in mobile cloud architectures. The proposed system ensures message integrity and unverifiability through a blockchain-based method for BIM data aggregation. BCT greatly improves the security and quality of BIM data and expect bcBIM to be an inevitable trend with the development of mobile devices, cloud computing, IoT and BIM big data sharing.

Liang *et al.* (2017) proposed a decentralized and trusted cloud data provenance architecture, ProvChain, using BCT. The aim of ProvChain is to provide tamper-proof records, increase transparency, privacy and availability of the provenance data in the cloud. The system operates in 3 phases: data collection, storage and validation. ProvChain can be extended to different use cases and data units in cloud storage. Future work includes developing ProvChain for federated cloud providers and collecting data provenance across different providers and storage applications. The validation currently uses Tierion an application programming interface (API), but the aim is to implement it using an open-source architecture to improve performance, security and flexibility. The provenance data would also be used to check for access control violations to better protect the cloud storage application (Liang *et al.*, 2017).

Emphasizing the importance of connecting database and workflow provenance to understand the origin of results in scientific applications is something inevitable (Davidson and Freire, 2008). Bahga and Madisetti (2016) presented a peer-to-peer platform named BPIIoT for Industrial Internet of Things (IoT) based on BCT. The platform enables a marketplace of manufacturing services where the machines have their own BCT accounts and users can interact with machines directly. Benefits of using BCT for Industrial IoT include decentralization, trustlessness, resilience, scalability, security and auditability. Challenges in widespread adoption of the technology include trade-offs between consistency and availability, smart contract vulnerabilities, lack of awareness and regulatory hurdles (Bahga and Madisetti, 2016).

In the context of data management, there is a distinction between on-chain and off-chain data. On-chain data refer to information that is directly stored within the blockchain itself, utilizing the distributed ledger technology for storage, verification and immutability. Off-chain data, on the other hand, refer to information that resides outside the blockchain network, often stored in external systems, which accessed through oracles. Both on-chain and off-chain data sources play a crucial role in creating a comprehensive and robust asset management ecosystem, leveraging the strengths of BCT while integrating with external data sources and processes (Shojaei *et al.*, 2020; Suhail *et al.*, 2022; Hellenborn *et al.*, 2023; Sadri *et al.*, 2023).

3. Materials and methods

Qualitative research data were obtained from a wide range of secondary sources of data using scoping review. Afterward, interviews were conducted to the industry specialists as primary source of data. Following the completion of the analyses, the resulted information has been facilitated for the development of a model for blockchain-based DT data provenance focusing on PAM in building facilities. Assessment of the proposed model of data provenance on blockchain-based DT was based on a scenario as part of the case study involving the Remix Ethereum platform and Sepolia testnet. The research methodology is presented in Figure 1.

3.1 Scoping review

A scoping review was conducted to map the foundational concepts, primary sources, and types of evidence relevant to the study field. This review was undertaken to establish the theoretical model for the present study. Google Scholar was selected as the database for the review, and various search terms were employed to gather data from diverse and pertinent fields related to the current research.

(1) ("Blockchain" OR "BCT") AND ("Provenance" OR "Data Provenance") AND ("Predictive Asset Management" OR "Asset Management" OR "Asset Information Model" OR "Asset Information Requirements") AND ("Building facility" OR "Facility management")

(2) ("Blockchain" OR "BCT") AND ("Digital Twin" OR "DT") AND ("Predictive Asset Management" OR "Asset Management" OR "Asset Information Model" OR "Asset Information Requirements") AND ("Smart Contract" OR "Decentral Application" OR "DApp")

The process of selection followed the guidelines of PRISMA-ScR (Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews) (Tricco *et al.*, 2018). In total, 481 papers were identified based on the mentioned strings. Twenty-two searches were selected for scoping review by eliminating the duplicates, screening titles, abstracts and conclusions, accessed to the full text, and filtering according to year of publication: 2016–2022, and language of English. Figure 2 represents the process of research based on the classification, filters and modification. According to the selected articles, 5 additional references were added for additional explanation for further discussions.

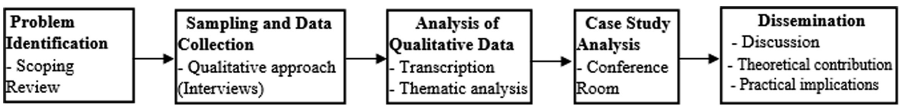

Figure 1.
Research methodology

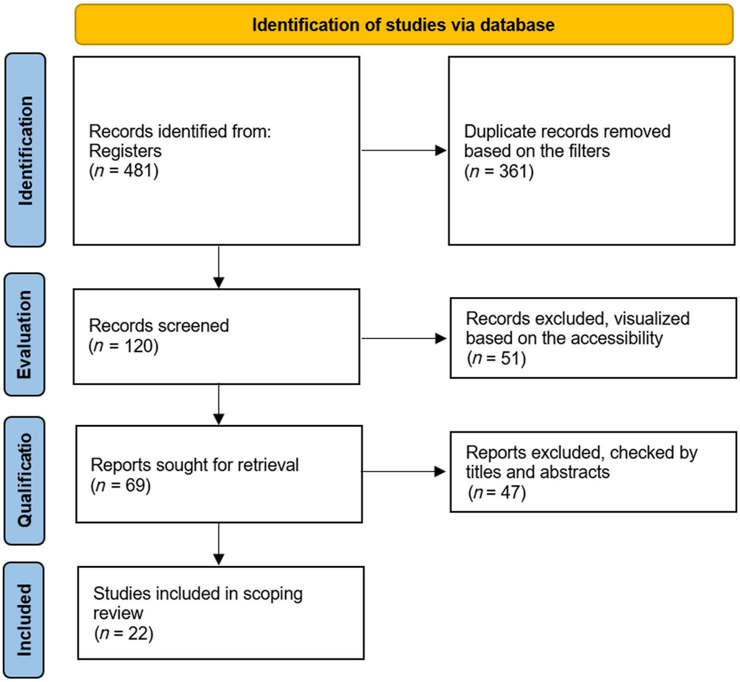

Figure 2.
PRISMA – ScR flow diagram

3.2 Interviews

To gain insights from industry experts, semi-structured interviews were conducted over video calls, and all interviews were recorded and transcribed with the interviewees' consent. The interview questions were formulated by the authors, using a guide that encompasses diverse themes encouraging an open and adaptive discussion. This guide, informed by the recent literature in the field, was designed to address the main research questions of this study. The demographics of the interviewees are displayed in Table 1. Interviewees were chosen from a professional networking platform (LinkedIn) based on blockchain and DT specialists in the industry all around the world, especially including people who have been familiar with building facilities. An interview invitation was sent to 19 individuals but 8 of them agreed to participate. To analyze the collected data thematically, qualitative data analysis software NVivo was utilized.

3.3 Case study

This research investigates the indoor environment comfort-level indicators in an 18 square meters conference room located in Stockholm belonging to Pythagoras AB company as shown in Figure 3. Sensor data, including day, hour, occupancy, temperature, CO_2 level and humidity, have been collected to analyze the environmental conditions within the office space. The focus of this case study is to develop a smart contract between FM and Owners using the Remix platform, enabling the input of data into the smart contract, and providing users with the ability to visualize the status of the conditions and make required decisions based on the predictive analysis.

Table 1.
Interviewees' demographics

Position (role)	Type of organization	Company size*	Operation region	Years of experience	Duration**
Digital twin specialist	Metaverse consultancy	Small (30)	Gothenburg	20	65
CEO	IT Services and IT Consulting	Small (16)	Slovakia	25	61
CEO	IT Services and IT Consulting	Small (10)	England	20	57
Digitalization sustainability manager	construction and infrastructure business	Medium (125)	Norway	5	59
Chief architect	IT Services and IT Consulting	Large (10000)	San Francisco	30	62
CSO	IT Services and IT Consulting	Small (20)	Germany	12	55
Senior lecturer	Higher Education	Medium (150)	Ireland	38	58
Post-doctoral fellow	Higher Education	Large (10000)	Canada	12	60

Note(s): *Small: 0–50 employees, Medium: 50–250 employees, Large: 250+ employees. **Interview duration in minutes

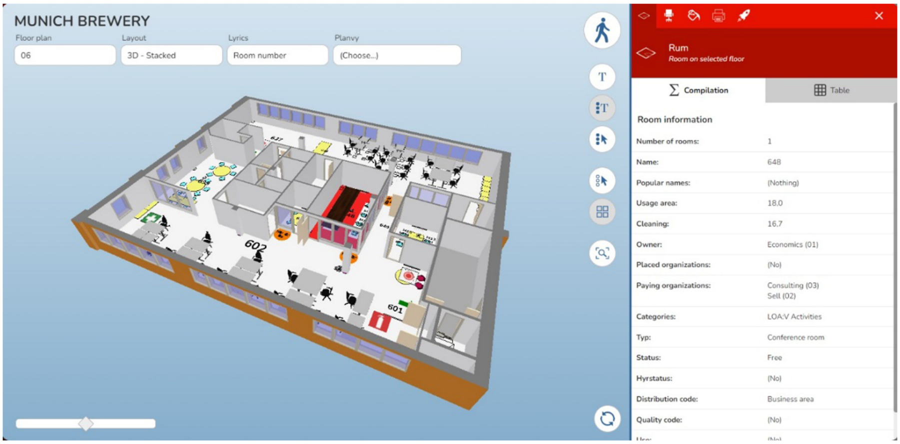

Figure 3.
Case study involving conference room information

The smart contract encompasses various functions, such as "Add Room Data," which allows users to input data such as day, hour, occupancy (no limit), CO2 level (range 300ppm–1000ppm), temperature (range 20°C–25°C) and humidity (range 40%–60%) into the contract; "Get Environment Status" function that checks if the sensor data fall within predefined ranges by using programmed thresholds. This check is done when specific day and hour values are provided; "Get Room Data," which retrieves historical sensor data based on specified day and hour inputs; "Predict Environment," which alerts users regarding asset adjustment status as shown in Table 2 and Figure 4.

Dynamic data including occupancy, temperature, CO_2 level and humidity are extracted continuously over a 24-hour period, representing key parameters during the O&M phase of the DT. These data have been utilized in predictive maintenance, encompassing visualization, data management, result analysis and anomaly detection. Smart contracts can be customized to leverage these data for PAM. For this case study, the identified needs revolve around data storage and visualization, retrieving asset status for informed decision-making and receiving alert notifications for proactive predictive maintenance activities. These requirements customized the smart contract for coding and implementing a system that effectively utilizes the collected data for predictive maintenance purposes.

The compiled smart contract is deployed on a Sepolia testnet to ensure transaction confirmation and approval within the blockchain framework. Remix Ethereum is a browser-based compiler and Integrated Development Environment for Solidity, the programming language used for writing smart contracts on the Ethereum blockchain. It offers a user-friendly interface for developing, testing and deploying contracts on Ethereum Virtual Machine (EVM). The Sepolia testnet is a public Ethereum test network that enables developers to test their smart contracts and DApps without incurring real costs (Celik *et al.*, 2023; Wöhrer and Zdun, 2021).

4. Results

4.1 Thematic analysis—interviews

Themes were coded based on research questions and the descriptions were represented based on interviews as indicated in Table 3. The integration of blockchain technology in asset management offers benefits such as trustworthy information, improved transparency, increased security, greater efficiency and enhanced predictive analytics. Standardization, data provenance, data synchronization, asset representation and metadata management are crucial considerations in implementing a successful blockchain platform. Challenges include data volume, integration from various sources and the need for cooperation among IT suppliers. Overall, based on interview results, blockchain technology revolutionizes asset management by providing reliable data, transparency and efficient processes.

4.2 Deployment of smart contract

The focus of this case study is to create a platform that enables the storage of crucial data obtained from a DT including sensor information on the -blockchain. This platform serves the purpose of facilitating PAM and detecting asset status through the implementation of smart contracts. For this purpose, a smart contract has been developed using the Remix Ethereum platform and Solidity programming language (Figure 5). To deploy the smart contract, it is needed to compile and run the script on the Remix platform solidity compiler and by choosing the Injected Provider MetaMask as a deployed Environment, after deploying the script, a

Range	Functions Add room data	Get environment status	Get room data	Predictive maintenance
	Day	Call	Call	Call
	Hour			
No limit	Occupancy	Retrieve	Retrieve	Retrieve
300ppm–1000ppm	CO2 level			
20℃–25℃	Temperature			
40%–60%	Humidity			

Table 2.
Functions and input data of smart contract

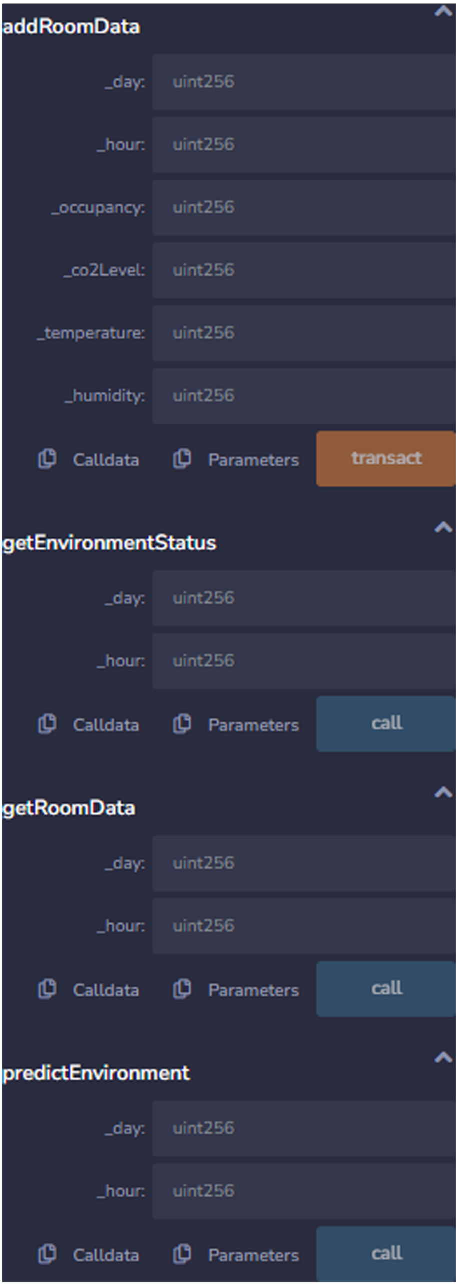

Figure 4.
Add room data and retrieve functions

confirmation through MetaMask (which is a web-based cryptocurrency wallet) required for transaction permission (Celik *et al.*, 2023). Upon confirmation of the transaction on the Sepolia testnet (Fernandes and Werner, 2023) using MetaMask, transaction details such as

Themes	Descriptions
1. Significance of blockchain technology in Asset Management	- As a facility manager: trustworthy information needed to be hunted regarding any conflict action - Improved transparency: BCT can provide greater transparency into asset ownership, transactions, and other key data. This can help prevent fraud, reduce errors, and improve data quality - Increased security: BCT is highly secure, using cryptographic algorithms and distributed ledgers to ensure that data is protected from tampering or hacking - Greater efficiency: By enabling automated and decentralized transactions, BCT can improve the speed and efficiency of asset management processes - Improved tracking and traceability: With blockchain, asset managers can track assets more effectively throughout their lifecycle, from acquisition to disposition. This can help improve the accuracy of asset valuations and reduce the risk of errors or fraud - Enhanced predictive analytics: With blockchain, asset managers can collect and analyze data from a range of sources to develop predictive models that can help anticipate maintenance needs, identify potential issues before they arise, and optimize asset utilization
2. The necessity of Data Provenance	- The need of standardization for dynamic data that created and transfer on blockchain platform - Merging and collaborating the required dynamic data from asset information model and providing the accessibility for smart contract implementation - Quality assurance of data, Traceability of assets, and facilitating Decision making
3. Processes of establishment of data provenance on blockchain-based DT	- First step: data collection, Second step: data tagging, Third step: data validation, Forth step: data processing and storage, Fifth step: usage for prediction purposes
4. The structure of required dynamic data for implementing on blockchain platform	- Tagged data or data passports on assets like location, status, time of installation, the way of installation, the organization who installed, and how it is been working during its lifetime - Proper strategy for sync data continuously and keeping blockchain up to date - The structure of required data containing, event log of validation and history of decisions and maintenance, and predictive models
5. Organization of data provenance for utilizing in different aspects	- Creation of a model that is scalable, interoperable, and composable for representing assets in 3D - Metadata management, conducting data audits, data visualization, traceability, and validation

(*continued*)

Table 3. Themes and descriptions of interviews

Themes	Descriptions
6. Potential benefits of data provenance on blockchain-based DT	- Data manipulation avoidance - The synergies between blocks of blockchain providing the reliability to eliminate the third parties from the scene - Increasing of data quality and traceability, data structuring and visualization
7. Challenges and prerequisites for implementation of data provenance on blockchain-based DT	- Time and cost for implementing blockchain - No cooperating and competing IT suppliers - No full implementation in data synchronization infrastructure - Data volume, and integration of them from various resources

Table 3.

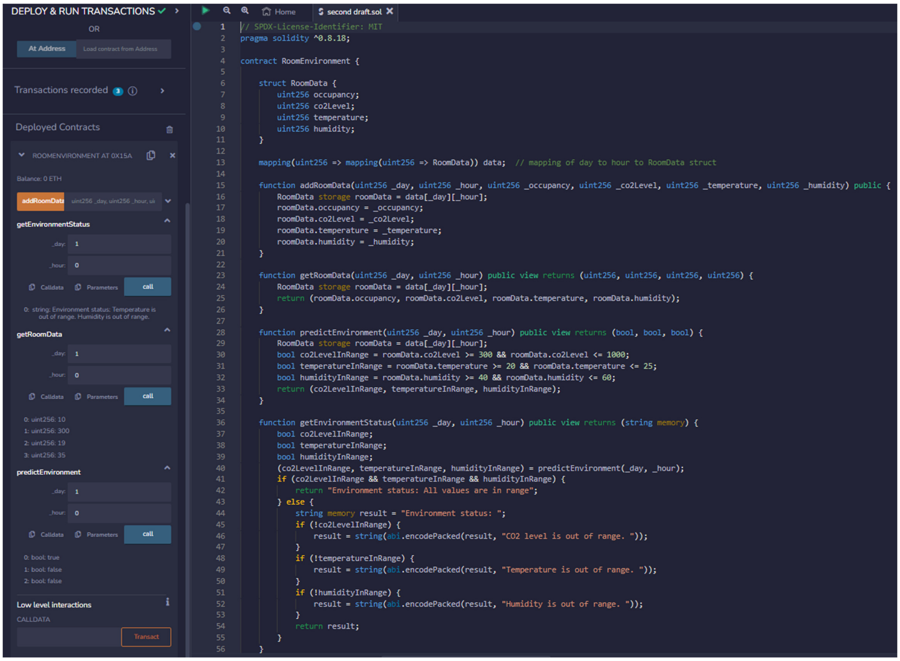

Figure 5.
Smart contract using Remix Ethereum platform

transaction hash (that could be used for tracking), status (that shows the transaction has been successful or not), block number (that shows on which block the transaction has been stored), timestamp (date and time of the transaction), contract address (origin and destination of transaction) and transaction fee are displayed on Etherscan, which is a leading Ethereum blockchain explorer (Figure 6).

To utilize the smart contract within an individual API, it is necessary to link a server to the front end and user interface and establish a connection between the smart contract and the users. The server is created using the express package and JavaScript programming language. The API is designed to incorporate three buttons: "connect to MetaMask," "connect

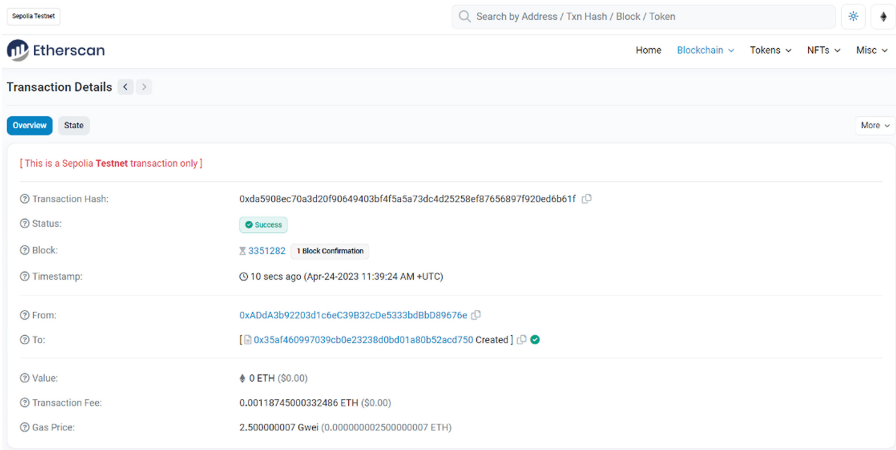

Figure 6.
Etherscan transaction details

to contract" and "get data from contract." The API's Index.html code includes the implementation of the Application Binary Interface (ABI) and the contract's hash from Remix Ethereum.

5. Discussion

Three key areas were focused on the application of data provenance model on Blockchain-based DT for PAM in building facilities. First, the workflow of blockchain implementation was examined, highlighting the necessary steps involved in integrating BCT into asset management systems. Second, the establishment of the required data in data provenance was discussed, emphasizing the significance of collecting and validating accurate and reliable information about assets throughout their lifecycle. Lastly, the limitations associated with blockchain-based DT were addressed. The interview's results emphasize the collaboration of dynamic data from AIMs and its accessibility for smart contracts. The key objectives include ensuring data quality, asset traceability and facilitating decision-making, which are the responses to RQ1. The process involves data collection, tagging, validation, processing, storage and eventual usage for prediction purposes. The tagged data or data passports contain information such as asset location, status, installation details and maintenance history. It is crucial to establish a strategy for continuous data synchronization and blockchain updates. The required data structure includes event logs, validation records, decision history and predictive models. Additionally, the creation of a scalable, interoperable, and composable 3D representation model for assets is essential. Metadata management, data audits, visualization, traceability and validation are also integral components, which are the responses to RQ1 and RQ2. Synergies within blockchain blocks eliminate the need for intermediaries. This leads to improved data quality, traceability and visualization. The challenges and prerequisites for implementing data provenance on blockchain-based digital transformation include the time and cost associated with blockchain implementation, the absence of cooperation among IT suppliers, incomplete implementation of data synchronization infrastructure, managing large data volumes and integrating data from diverse sources, which are the responses to RQ3.

5.1 Process map of blockchain implementation

The decentralized and automated nature of BCT improves the speed and efficiency of asset management processes by reducing delays, bureaucracy and associated costs. The use of BCT also allows for improved tracking and traceability of assets throughout their lifecycle. Facility managers can accurately track asset acquisition, maintenance history, repairs, and disposal, improving the accuracy of asset valuations and reducing the risk of errors or fraud (Ramachandran and Kantarcioglu, 2017; Sahal *et al.*, 2021). Additionally, blockchain facilitates enhanced predictive analytics by collecting and analyzing data from various sources, allowing facility managers to develop predictive models that anticipate maintenance needs, identify potential issues in advance, and optimize asset utilization.

The flow chart in Figure 7 outlines the process of receiving required data from DT and storing it on a blockchain database. This data can include live information about asset specifications, maintenance schedules, sensor readings and other relevant details. Data would be stored on an off-chain cloud storage which is in contact with PAM (AI algorithm) for prediction and provide necessary data for implementation on blockchain platform. The data are transmitted securely, ensuring its integrity and privacy. Smart contracts are executed to validate and process the data by Ethereum Virtual Machine (EVM) that is connected to MetaMask, while nodes confirmations provide consensus and decentralization. The flow then moves to interacting with a DApp or an API, enabling integration with distributed ledgers. Users, such as facility managers, can utilize the DApp or API to maintain assets in building facilities, accessing information, tracking maintenance schedules and leveraging additional functionalities provided by the system and at the end the updated maintenance information would be transferred on DT (Tezel *et al.*, 2020).

5.2 Establishment of required data in data provenance

In the context of implementing a blockchain platform, several important considerations arise. Standardization is a critical aspect for effectively handling dynamic data generated and transferred within the blockchain ecosystem. By merging and collaborating the necessary dynamic data from AIMs, we can enhance accessibility for smart contract implementation, enabling seamless interactions and automation. Data provenance plays a vital role in

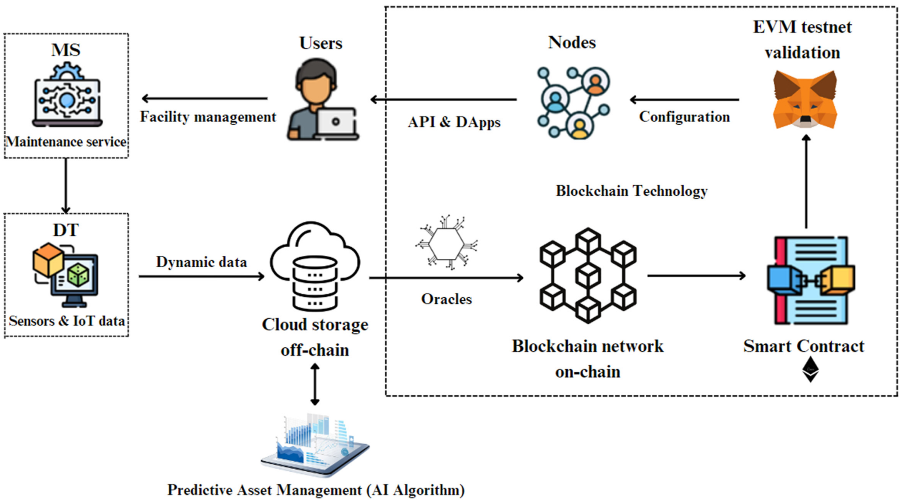

Figure 7.
Implementation of data provenance model on blockchain-based DT

ensuring the quality, traceability, and reliability of assets. It encompasses key aspects such as quality assurance, traceability of assets, collaborative development and facilitating decision-making processes (McNamara and Sepasgozar, 2021). To achieve effective data provenance, a structured approach is essential. The process involves distinct steps, starting with data collection, followed by data tagging, validation, processing and storage and ultimately leveraging the data for prediction purposes. Tagged data or data passports are assigned to assets, capturing vital information such as location, status, installation details, responsible organizations, and operational performance throughout their lifespan (Shojaei, 2019). These data markers provide a comprehensive understanding of asset attributes and history.

Live data or dynamic data that required for predictive purposes can be stored as On-chain data, which is stored directly within the blockchain, utilizing distributed ledger technology for storage, verification, and immutability. Off-chain data, however, exists outside the blockchain network and is typically stored in external systems, accessed through oracles (Figure 6). Both on-chain and off-chain data sources are essential for creating a comprehensive and robust asset management ecosystem. This approach leverages the strengths of blockchain technology while integrating with external data sources and processes (Hellenborn *et al.*, 2023; Sadri *et al.*, 2023).

Ensuring continuous synchronization and maintaining an up-to-date blockchain requires a proper strategy for data synchronization. This entails developing mechanisms for seamless integration and data exchange between various systems, as well as keeping the blockchain network synchronized with the latest data updates. The structure of the required data can encompass various components, including an event log capturing validation activities and historical decisions, records of asset maintenance and management and predictive models that utilize the data for forecasting and optimization.

Creating a scalable, interoperable and composable model for representing assets in three dimensions (3D) is important. This model should accommodate diverse asset types and enable seamless integration with other systems and processes. To further enhance the system, effective metadata management, data audits, data visualization capabilities, traceability mechanisms and validation processes should be in place. These measures contribute to the reliability and integrity of the data within the blockchain ecosystem.

Overall, implementing a blockchain platform requires careful consideration of standardization, data provenance, data synchronization, asset representation, metadata management and the integration of on-chain and off-chain data sources. By addressing these considerations, organizations can build a robust and efficient asset management ecosystem that leverages the strengths of BCT while incorporating essential data from various sources to enhance decision-making, traceability and operational optimization.

5.3 Research implication

The implications of this research are substantial for professionals overseeing FM and asset maintenance. Through the integration of blockchain technology, real-world applications can redefine how performance FM is approached. For managers, this creates the opportunity to have an unalterable and transparent record of asset data, which in turn builds confidence in decision-making. This newfound reliability empowers managers to fine-tune asset utilization and predict maintenance requirements using cutting-edge predictive analytics. The result is a more efficient operation that translates to tangible cost savings. Additionally, blockchain's role extends to enhancing predictive maintenance practices. By ensuring data credibility and real-time updates, potential issues can be spotted early, allowing timely interventions and reduced downtime. This research essentially opens doors to a fresh era of practical asset management, offering concrete solutions for better operational outcomes.

5.4 Limitations

Effectively managing large volumes of data is essential in this context. To address this challenge, a combination of off-chain and on-chain databases can be utilized, allowing organizations to store and process data both on the blockchain and external databases. This enables efficient storage, retrieval, and processing mechanisms to handle the increasing data load (Sadri *et al.*, 2023).

It is important to acknowledge the limitations of this research study, such as potential constraints in data collection from the industry, resulting in a limited number of conducted interviews. The scope of the thesis study may have primarily focused on PAM data, which could have limited the breadth of insights obtained. Nevertheless, by meeting the prerequisites and addressing these limitations, organizations can fully unlock the potential of data provenance on a blockchain-based DT. The transparent audit trail provided by blockchain facilitates data traceability, while standardization and data tagging improve data structuring and visualization. Overcoming challenges like managing large data volumes and ensuring data integration will lead to improved insights and operational efficiency.

6. Conclusion

The integration of data provenance technology with blockchain-based DT holds significant promise for advancing PAM in building facilities. By leveraging the capabilities of blockchain, facility managers can benefit from improved transparency, enhanced security, greater efficiency and enhanced tracking and traceability of assets. BCT offers a decentralized and tamper-proof database that ensures trustworthy and transparent information, enabling facility managers to access reliable data for making informed decisions. The use of cryptographic algorithms and distributed ledgers provides a high level of security, protecting asset-related data from unauthorized access or tampering. Moreover, the automation and decentralization provided by BCT streamline asset management processes, reducing delays and associated costs. The ability to accurately track and trace assets throughout their lifecycle enhances the accuracy of asset valuations and minimizes the risk of errors or fraudulent activities. Additionally, blockchain enables predictive analytics by collecting and analyzing data from various sources, empowering facility managers to anticipate maintenance needs, proactively address potential issues and optimize asset utilization.

To implement a successful Data Provenance on blockchain-based DT in building facilities, it is essential to address the key prerequisites such as implementing BCT, fostering collaboration among IT suppliers, establishing robust data synchronization infrastructure, and effectively managing large volumes of data. By overcoming these challenges, organizations can harness the full potential of data provenance on a blockchain-based DT, leading to improved insights, operational efficiency, and informed decision-making. The integration of off-chain and on-chain databases offers a comprehensive solution to tackle data volume issues effectively. Also, for organizing data provenance it is essential to develop a 3D asset model that is flexible, compatible with different systems and allows for easy customization. Alongside this, it is crucial to effectively manage metadata, conduct data audits to ensure accuracy, visualize data for better understanding, track asset movements for traceability, and validate information for reliability. Overall, the implementation of blockchain-based DT in the context of data provenance presents a promising avenue for transforming asset management practices in building facilities, promoting transparency, reliability and optimal performance.

References

Bahga, A. and Madisetti, V.K. (2016), "Blockchain platform for industrial internet of things", *Journal of Software Engineering and Applications*, Vol. 9 No. 10, doi: 10.4236/jsea.2016.910036.

Bew, M. and Richards, M. (2008), "Bew-Richards BIM maturity model", *BuildingSMART Construct IT Autumn Members Meeting*, Brighton.

Bouabdallaoui, Y., Lafhaj, Z., Yim, P., Ducoulombier, L. and Bennadji, B. (2021), "Predictive maintenance in building facilities: a machine learning-based approach", *Sensors*, Vol. 21 No. 4, doi: 10.3390/s21041044.

Casino, F., Dasaklis, T.K. and Patsakis, C. (2019), "A systematic literature review of blockchain-based applications: current status, classification and open issues", *Telematics and Informatics*, Vol. 36, doi: 10.1016/j.tele.2018.11.006.

Celik, Y., Petri, I. and Barati, M. (2023), "Blockchain supported BIM data provenance for construction projects", *Computers in Industry*, Vol. 144, doi: 10.1016/j.compind.2022.103768.

Davidson, S.B. and Freire, J. (2008)), "Provenance and scientific workflows: challenges and opportunities", *Proceedings of the 2008 ACM SIGMOD international conference on Management of data*, pp. 1345-1350, doi: 10.1145/1376616.1376772.

Fernandes, F. and Werner, C. (2023), "Towards a blockchain-based software engineering education", *arXiv Preprint*, arXiv:2304.04549, doi: 10.48550/arXiv.2304.04549.

Götz, C.S., Karlsson, P. and Yitmen, I. (2020), "Exploring applicability, interoperability and integrability of Blockchain-based digital twins for asset life cycle management", *Smart and Sustainable Built Environment*, Vol. 11 No. 3, doi: 10.1108/SASBE-08-2020-0115.

Hastig, G.M. and Sodhi, M.S. (2020), "Blockchain for supply chain traceability: business requirements and critical success factors", *Production and Operations Management*, Vol. 29 No. 4, doi: 10.1111/poms.13147.

Hellenborn, B., Eliasson, O., Yitmen, I. and Sadri, H. (2023), "Asset information requirements for blockchain-based digital twins: a data-driven predictive analytics perspective", *Smart and Sustainable Built Environment*, Vol. ahead-of-print No. ahead-of-print, doi: 10.1108/SASBE-08-2022-0183.

Jabbar, S., Lloyd, H., Hammoudeh, M., Adebisi, B. and Raza, U. (2021), "Blockchain-enabled supply chain: analysis, challenges, and future directions", *Multimedia Systems*, Vol. 27, pp. 787-806, doi: 10.1007/s00530-020-00687-0.

Kuperberg, M. and Geipel, M. (2021), "Blockchain and BIM (building information modeling): progress in academia and industry", *arXiv Preprint*, arXiv:2104.00547, doi: 10.48550/arXiv.2104.00547.

Lee, D., Lee, S.H., Masoud, N., Krishnan, M.S. and Li, V.C. (2021), "Integrated digital twin and blockchain framework to support accountable information sharing in construction projects", *Automation in Construction*, Vol. 127, doi: 10.1016/j.autcon.2021.103688.

Liang, X., Shetty, S., Tosh, D., Kamhoua, C., Kwiat, K. and Njilla, L. (2017), "Provchain: a blockchain-based data provenance architecture in cloud environment with enhanced privacy and availability", *2017 17th IEEE/ACM International Symposium on Cluster, Cloud and Grid Computing (CCGRID)*, IEEE, pp. 468-477, doi: 10.1109/CCGRID.2017.8.

McNamara, A.J. and Sepasgozar, S.M. (2021), "Intelligent contract adoption in the construction industry: concept development", *Automation in Construction*, Vol. 122, doi: 10.1016/j.autcon.2020.103452.

Petrović, E.K., Brent, A.C., Iorns Magallanes, C., Hamer, L. and van Eijck, D. (2022), "Blockchain for supply chain ledgers: tracking toxicity information of construction materials", in *Blockchain for Construction*, Springer Nature Singapore, Singapore, pp. 89-111, doi: 10.1007/978-981-19-3759-0_6.

Putz, B., Dietz, M., Empl, P. and Pernul, G. (2021), "Ethertwin: 'blockchain-based secure digital twin information management'", *Information Processing and Management*, Vol. 58 No. 1, doi: 10.1016/j.ipm.2020.102425.

Ramachandran, A. and Kantarcioglu, D.M. (2017), "Using blockchain and smart contracts for secure data provenance management", *arXiv Preprint*, arXiv:1709.10000, doi: 10.48550/arXiv.1709.10000.

Sadri, H., Yitmen, I., Tagliabue, L.C., Westphal, F., Tezel, A., Taheri, A. and Sibenik, G. (2023), "Integration of blockchain and digital twins in the smart built environment adopting disruptive technologies—a systematic review", *Sustainability*, Vol. 15 No. 4, doi: 10.3390/su15043713.

Sahal, R., Alsamhi, S.H., Brown, K.N., O'shea, D., McCarthy, C. and Guizani, M. (2021), "Blockchain-empowered digital twins collaboration: smart transportation use case", *Machines*, Vol. 9 No. 9, doi: 10.3390/machines9090193.

Sepasgozar, S.M., Khan, A.A., Smith, K., Romero, J.G., Shen, X., Shirowzhan, S., Li, H. and Tahmasebinia, F. (2023), "BIM and digital twin for developing convergence technologies as future of digital construction", *Buildings*, Vol. 13 No. 2, doi: 10.3390/buildings13020441.

Shakila, U.K. and Sultana, S. (2021), "A decentralized marketplace application based on ethereum smart contract", *2021 24th International Conference on Computer and Information Technology (ICCIT)*, IEEE, pp. 1-5, doi: 10.1109/ICCIT54785.2021.9689879.

Shojaei, A. (2019), "Exploring applications of blockchain technology in the construction industry", in Ozevin, D., Ataei, H., Modares, M., Gurgun, A.P., Yazdani, S. and Singh, A. (Eds), *Proceedings of International Structural Engineering and Construction*, Vol. 6, ISBN: 978-0-9960437-6-2.

Shojaei, A., Wang, J. and Fenner, A. (2020), "Exploring the feasibility of blockchain technology as an infrastructure for improving built asset sustainability", *Built Environment Project and Asset Management*, Vol. 10 No. 2, pp. 184-199.

Stojanovic, V., Trapp, M., Klimke, J., Richter, R. and Döllner, J. (2022), "Private distributed ledger for indoor scene annotation", in *Blockchain for Construction*, Springer Nature Singapore, Singapore, pp. 185-206.

Suhail, S., Hussain, R., Jurdak, R. and Hong, C.S. (2021), "Trustworthy digital twins in the industrial internet of things with blockchain", *IEEE Internet Computing*, Vol. 26 No. 3, doi: 10.1109/MIC.2021.3059320.

Suhail, S., Hussain, R., Jurdak, R., Oracevic, A., Salah, K., Hong, C.S. and Matulevičius, R. (2022), "Blockchain-based digital twins: research trends, issues, and future challenges", *ACM Computing Surveys (CSUR)*, Vol. 54 No. 11s, pp. 1-34, doi: 10.1145/3517189.

Tezel, A., Papadonikolaki, E., Yitmen, I. and Hilletofth, P. (2020), "Preparing construction supply chains for blockchain technology: an investigation of its potential and future directions", *Frontiers of Engineering Management*, Vol. 7, pp. 547-563, doi: 10.1007/s42524-020-0110-8.

Tricco, A.C., Lillie, E., Zarin, W., O'Brien, K.K., Colquhoun, H., Levac, D., Moher, D., Peters, M.D., Horsley, T., Weeks, L. and Hempel, S. (2018), "PRISMA extension for scoping reviews (PRISMA-ScR): checklist and explanation", *Annals of Internal Medicine*, Vol. 169 No. 7, pp. 467-473, doi: 10.7326/M18-0850.

Wöhrer, M. and Zdun, U. (2021), "Devops for ethereum blockchain smart contracts", *2021 IEEE International Conference on Blockchain (Blockchain)*, IEEE, pp. 244-251, doi: 10.1109/Blockchain53845.2021.00040.

Yaqoob, I., Salah, K., Uddin, M., Jayaraman, R., Omar, M. and Imran, M. (2020), "Blockchain for digital twins: recent advances and future research challenges", *IEEE Network*, Vol. 34 No. 5, pp. 290-298, doi: 10.1109/MNET.001.1900661.

Zheng, R., Jiang, J., Hao, X., Ren, W., Xiong, F. and Ren, Y. (2019), "bcBIM: a blockchain-based big data model for BIM modification audit and provenance in mobile cloud", *Mathematical Problems in Engineering*, Vol. 2019, doi: 10.1155/2019/5349538.

Further reading

Etherscan (2023), available at: https://etherscan.io/

EtherTwin DApp, available at: https://github.com/sigma67/ethertwin (accessed 2023).

EthSwarm DApp, available at: https://www.ethswarm.org/ (accessed 2023).

Montecchi, M., Plangger, K. and Etter, M. (2019), "It's real, trust me! Establishing supply chain provenance using blockchain", *Business Horizons*, Vol. 62 No. 3, pp. 283-293, doi: 10.1016/j.bushor.2019.01.008.

Pythagoras AB, available at: https://www.pythagoras.se/ (accessed 2023).

Remix (2023), available at: https://remix-ide.readthedocs.io/en/latest/ (accessed 2023).

Tierion API, available at: https://tierion.com/app/api

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