Computers in Industry 144 (2023) 103768

Contents lists available at ScienceDirect

Computers in Industry

journal homepage: www.sciencedirect.com/journal/computers-in-industry

Blockchain supported BIM data provenance for construction projects

Yasin Celik [a,*], Ioan Petri [a], Masoud Barati [b]

[a] The Parade, Cardiff, CF24 3AA, Queen's Building, School of Engineering, Cardiff University, UK
[b] Newcastle upon Tyne, Newcastle, NE1 7RU, School of Computing, Newcastle University, UK

ARTICLE INFO

Keywords:
Blockchain
Data provenance
BIM
Construction project

ABSTRACT

The management of construction projects requires adequate techniques to support the continual exchange of information across disciplines. Recent advances in Building Information Modelling (BIM) have exposed new ways for process and data integration with open data formats, process mapping, and terminology. In construction projects where multiple disciplines produce and share BIM data, mechanisms for defining information priority, provenance and suitability become necessary in order to have consistent and traceable use of data. This includes objects or collection of attributes for data objects that are associated with a discipline or organisation including clear identification of the transaction that has introduced the information. Blockchain can be used to record metadata of BIM objects such as the issuing discipline, object version and responsibility/liability associated with the data. Blockchain can offer the capability to apply levels of "trust" to individual BIM objects and a more secured framework of collaboration across stakeholders.

This paper proposes a Blockchain-based BIM data provenance model to support information exchange in construction projects. By testing the solution in a real-world bridge construction scenario, it has been shown that the approach can recognise the levels of competence and can improve the process of BIM implementation. The proposed approach gives stakeholders more confidence when sharing their BIM data, reduces costs, and improves risk contingencies in construction projects. The paper provides a cost analysis to evidence the implications of using Blockchain for BIM data provenance through an experimental framework supported by an Ethereum public test network. A front-end web page has also been created to facilitate interaction with smart contracts and to monitor the BIM data provenance process.

1. Introduction

Digitisation of the construction sector has been triggered by the recent advancements in information technology that have created unprecedented possibilities for the development of innovations and applications for Construction (Brennen and Kreiss, 2014; Slaughter, 1998; Elghaish et al., 2020). Building Information Modelling (BIM) represents a major advancement in the construction industry (Murphy, 2014). BIM is often described as a "database with drawings" that provides an information repository or guideline of the constructed assets which can be used for operating purposes for its entire project lifecycle from preparation to maintenance and demolition (Morgan, 2017).

Numerous international initiatives have been launched by industry and governmental organisations in the building and facility management sector to integrate BIM with various construction applications (Namli et al., 2019). Digital representations of a real construction asset (i.e. building) can be realised through the use of BIM, from construction planning through building activity, to enable optimal communication and information exchange across all construction participants (Krämer and Besenyői, 2018). Such digital representations contribute to the development of a "digital twin (DT)" in the form of a data-driven dynamic representation of a construction asset that replicates its real-world behaviour (Lu et al., 2019). Information sharing in construction represents a challenging aspect involving data privacy and authenticity risks that often can have a negative impact on stakeholder trust, supply chain and asset management. Digital ledger solutions can reduce such risks and promote a higher order of collaboration across industrial stakeholders (Erri Pradeep et al., 2019a) (Opoku et al., 2021).

As reported by literature, there are several limitations associated with the use of BIM technologies, especially around integrated architectures which are often inadequate for real-time co-design, resulting in a lack of mechanisms for recording iterations associated with model modifications (Nawari, 2021). In particular, interoperability issues arise as a result of insufficient specifications when the model is shared across various project participants (disciplines) (Huahui and Deng, 2018). In addition, there are overlapping roles and responsibilities, protection of

* Corresponding author.
E-mail address: celiky@cardiff.ac.uk (Y. Celik).

https://doi.org/10.1016/j.compind.2022.103768
Received 17 May 2022; Received in revised form 7 July 2022; Accepted 15 August 2022
Available online 1 September 2022

intellectual property, a delegation of risk mitigation and confidentiality responsibilities, and accountability challenges (Nawari, 2021). BIM platforms are also exposed to vulnerabilities or cyber-attacks as a consequence of data manipulation, hacking, and other cyber-attacks (Yoon et al., 2021) requiring upgrades and modifications that can produce project delays and cost effects. A construction project also involves repetitive tasks that may be automated throughout the project's life cycle (Nawari and Ravindran, 2019) requiring transparency in the data collection process (Hijazi et al., 2019). Disinformation and communication failures can appear among project stakeholders involved in the project's implementation process (Bataw et al., 2016). As a result, the construction sector demands more adaptable and scalable data exchanges centred on BIM and the Common Data Environment (CDE), as well as increased resistance against manipulation of data, model integrity, and data provenance records (Morgan, 2017; Yoon et al., 2021).

On the other hand, the use of Blockchain for construction projects represents a key contribution toward the decentralisation and digitalisation of the sector. Blockchain uses a distributed public ledger with a shared and synchronised database for recording transactions while offering a strong mechanism for data provenance for BIM supported projects (Puthal et al., 2018).

It is conducted a research-based examination into the usage of Blockchain for data provenance in BIM environments, focusing on smart contracts and their use for BIM model coordination. In this paper, a BIM data provenance system is presented that uses Blockchain technology to record events, data and transactions results from the development of a multidisciplinary construction project.

This paper aims to address the following objectives:

- To propose a framework for improving BIM data provenance through the use of Blockchain technology for multi-disciplinary construction projects;
- To demonstrate the integration of BIM and Blockchain technology by implementing a data provenance model for a real construction case study;

This study discusses the usage of Blockchain technology in the construction sector, outlining a functional BIM provenance framework for practitioners and decision-makers to manage activities across the design, construction, and documentation stages. An analysis was made of the integration of Blockchain technologies into the BIM data environment to provide a higher level of digital reliability, integrity and transparency for construction projects. It is argued that emerging technologies such as Blockchain can contribute to the development of a more secure and digitised construction ecosystem, using evidence from an in-depth literature search and a real construction case study.

The remainder of the paper is as follows: Section 2 provides a background of the state-of-the-art developments of the industry, and Section 3 summarises research in the field of knowledge. The methodology for developing the data provenance is presented in Section 4, followed by a set of data provenance analyses and applications in Section 5. Section 6 validates the provenance model through a real-world case study involving the integration of Blockchain technology with the BIM environment of a multidisciplinary construction project. Sections 7 and 8 present the results and related implications of the proposed provenance model. Section 9 summarises the conclusions and discusses future work.

2. Related work

The increased interest in advancing automation in Construction has triggered the need for the identification of new methods to store and manage data. Due to the fact that the construction industry started to operate with digital representations of physical assets, data analytics for effective decision-making is needed to allow the interpretation and aggregation of data from various data sources. In particular, digital twins have the potential to incentivise the development of Building Information Modelling (BIM) in applications where identification and diagnosing of faults are needed. Additionally, digital twin technologies can lead to an increase in productivity, decrease the probability of failure, shorten manufacturing schedules, and provide new market opportunities (Patriarca et al., 2018).

Stakeholder engagement for the deployment of building technologies needs an integrated strategy to enhance collaboration between individuals, stakeholders and technology. BIM makes project data accessible to various users within the construction project at various stages including design and data management, simulations, and project scheduling (Keskin et al., 2020). One of the key BIM challenges is the identification of roles and responsibilities. Additional concerns include intellectual property protection, risk allocation, third-party safety and security, and the availability of technological intermediaries (Sacks et al., 2018).

The integration of BIM with Blockchain can enable a more transparent verification and storage of information related to the provenance of physical, digital, and application resources. Blockchain exposes a distributed ledger that is updated block-by-block at a time using a collaboratively selected validator. For a construction project, the Blockchain consensus process identifies a leader discipline that verifies that the selected leader has appropriate credentials, as well as that each node recognises the leader's block as a valid block for inclusion in the Blockchain (Christidis and Devetsikiotis, 2016). As the information submitted and verified in the chain is then disseminated and subsequently preserved across all nodes, Blockchain prevents data and copyright manipulation (Kshetri and Voas, 2018). The decentralisation of the Blockchain has been validated as a secure alternative to information storage, data processing, operation, and trust, providing a mechanism for managing data in digital environments with extensive security standards. While many sectors are actively exploring and analysing Blockchain technology and its uses, the construction sector's research is still in its infancy for adoption (McNamara and Sepasgozar, 2021).

Dongmin et al. (2021) designed a system for traceable data transfer that integrates digital twins and Blockchain technology. The authors validated the framework using a case study in which virtual positional data from a prefabricated brick is transferred in near real-time to the digital twin and stored on the Blockchain. The study findings demonstrate that the integration between a digital twin and Blockchain can improve the traceability of data transactions while enabling accountable data sharing about the project among stakeholders.

Tao et al. (2022) propose a collaborative design framework (CMF) based on Blockchain technology to promote data privacy. The article proposes an access control mechanism designed in CMF to safeguard critical BIM data stored on a Blockchain ledger from unauthorised access. New design methodologies in CMF have been established to aid in design coordination inside the access controlled Blockchain network. An illustrative design example verified the suggested CMF's practicality and performance with an appropriate latency and storage cost. Additionally, the findings indicate that when project participants interact inside the CMF, sensitive BIM data is successfully kept confidential. Xue and Lu (2020) introduce a new Semantic Differential Processing (SDT) approach to minimise information redundancy with BIM and Blockchain integration. The approach manages BIM changes as SDT records and compiles them into a consensus instead of storing the entire BIM or its signature code in the Blockchain.

A new BIM system model named bcBIM has been proposed to address information security in mobile cloud systems. The model proposes BIM data auditing for historical changes via Blockchain in the mobile cloud with big data sharing (Zheng et al., 2019). Sigwart et al. (2020) presents a Blockchain extensible IoT data provenance framework using smart contracts. Combined with Blockchain technologies, data provenance solutions are reliable instruments for making data more trustworthy while offering tamper-proof data on the sources and origin of data information. Liang et al. (2017) introduced ProvChain, with an architecture adapted for collecting and verifying the provenance of cloud data using Blockchain transactions with tamper-proof and user privacy features to verify the accuracy, integrity, and timeliness of provenance records. A window of latching (WoL) model is used to evaluate data provenance with advanced performance to monitor workload, security, and efficiency (Zhang et al., 2018).

3. Background information

This section presents an overview of the current state-of-the-art BIM solutions in the construction sector. Results of the literature review are presented and contextualised to demonstrate the importance of data provenance for construction digitalisation.

3.1. Digital twins using BIM data

Industrial processes have been significantly transformed over the last decade, owing to the remarkable spread of Cyber–Physical Systems (CPS), sophisticated data analytics, and high-performance computing technology. The recent advent of Digital Twinning (DT) strategies has proposed a virtual representation of a physical object, operation, system, or construction asset with a particular emphasis on the "smartness" of such virtual artifacts (Mohammadi and Taylor, 2017). Digital twins have emerged from the prevalence of sensor networks and the digitalisation of the manufacturing industry and production systems followed by applications in other sectors such as the construction industry. Digital twins operate with "digital replicas" that behave in the same way that their physical counterparts do in the actual world (Tao et al., 2018). Although developed to improve design and construction productivity at all stages of the lifecycle of construction, BIM has complementarity to digital twins in terms of tracking the physical asset and increasing the quality of operations in construction projects (Boje et al., 2020).

BIM systems address a general challenge of managing relevant data through interdisciplinary construction teams but with an insufficient trust among the various participants (Gu and London, 2010). A collaboration process facilitated by BIM creates security challenges across different professionals with different skills, knowledge and expertise. These problems are compounded by the fact that industries do not keep the same safety information and standards (Erri Pradeep et al., 2019b). In addition, data security is becoming more and more complex due to the differences between individuals interacting within a construction project and the development of the supply chain. The use of Blockchain technology can improve a project's Common Data Environment (CDE) with more secure management of activities resulting in full transparency of the project (Hammi and Bouras, 2018).

Blockchain contributes to the development of trust within an organisation through the use of authorised parties registered into a ledger (Brito and Castillo, 2013). A "distributed ledger" is used where each block of data is inextricably connected and replicated across a number of servers to enable more effective monitoring and management of contract documents (Nawari and Ravindran, 2019).

3.2. Provenance models – Issue Status and Blockchain

In construction projects, owners must be aware of the validity of the data, as well as modifications and access to data, at all stages of the project lifetime (Salman et al., 2018).

Provenance defines the surveillance chronology of an object (i.e., BIM) and refers to a process of monitoring various records of data obtained from a collaborative workflow. Provenance can be created by software in a specific physical, digital or application resource or can refer to an audit process that is operated on data created purely for the provenance information (Shetty et al., 2017). As such, the establishment of trust and confidence around data artefacts is ensured through the use of data-provenance systems (Garcia-Alfaro et al., 2015). Such systems provide information on different stages ranging from data creation and updates alongside the parties that have initiated the process and the origin of the data at different stages of the life cycle including the alteration of the data with the actors involved. In this respect, a data provenance scheme records unique data points and the operations identified with the data (Davidson and Freire, 2008), in a tamper-proof and reproducible manner (Hasan et al., 2009).

Blockchain technology provides the ability to protect data provenance and many required functionalities and features for auditable resources. The Blockchain Consensus mechanism selects a leader entity and ensures that the chosen leader has sufficient credentials and that each node accepts the leader's block as a suitable block to be included in the Blockchain (Christidis and Devetsikiotis, 2016). Blockchain provides mechanisms or instant updates for all users and facilitates integration with BIM technology including Digital twinning strategies.

3.3. Data disruption

Existing data traceability systems in Construction have significant issues with establishing verifiable data provenance and avoiding fraud and counterfeiting both in centralised and decentralised supply chains (Hastig and Sodhi, 2019). Construction risks providers (Tapscott and Vargas, 2019) estimate that 95% of construction project data is lost when a structure is handed over to the initial owner after project completion. According to Jabbar et al. (2020), the majority of existing digital construction solutions are still heavily reliant on centralised cloud infrastructures, resulting in a lack of transparency and an inability to protect against security risks such as reliability and auditability as well as data protection and privacy. Such issues can be addressed through the use of Blockchain which offers (i) secure traceability and control, (ii) data immutability, and (iii) the ability to build trust in extremely low-cost information technology solutions.

In Blockchain, users can choose which data to be stored in a block while also ensuring that identical copies of the data are distributed across the ledger (Nayak and Dutta, 2017). Blockchain has powerful mechanisms to handle authenticated users, ensuring accountability, scalability, and efficiency. Although at early adoption stages, Blockchain can deal with design-related data from a variety of disciplines ensuring integration and linking of data between project stakeholders (Al-Jaroodi and Mohamed, 2019). As the value of construction has increased as a consequence of, for example, mobile applications and sensors, Blockchain technologies may be leveraged to their benefit by providing new methods for authorisation and accessibility by stakeholders, suppliers, and the value chain (Al-Jaroodi and Mohamed, 2019). A data provenance architecture using Blockchain facilitates auditing of data events and can further improve access control policy enforcement based on authentication mechanisms (Nguyen et al., 2012).

3.4. Blockchain technology for construction automation

Construction projects use a variety of data and information that need to be stored, updated and consolidated. An improved management and analysis of construction data facilities quicker decision-making while also enhancing the quality of decision-making, resulting in better project quality and increased project profit. The use of BIM data comes with vulnerabilities around data modification or tracing revisions securely and persistence of revision history (Zheng et al., 2019). The process of recording project updates assumes the confidence of central operators that often can engage in improper activity leading to additional risks with data losses and inconsistencies. Such risks can be avoided with the seamless integration of BIM with Blockchain technology to empower collaboration and improve information flow between participative disciplines. Consequently, contractors and suppliers in the construction industry may depend on the collected data to establish the level of service quality standards. Blockchain has the potential

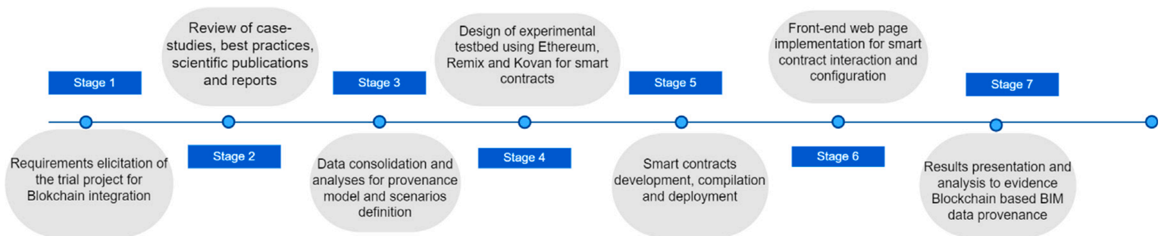


Fig. 1. Methodological stages.

to advance construction automation by integrating design records, and datasets from devices and organisations via the deployment of Blockchain records, thus enabling both historical record review and developmental research (Casino et al., 2019). An architect may be alerted when a design change occurs in a design project with information about the data encryption and transfer for storage. Project participants have complete control over their information and may authorise or remove access at any time, a process that is beneficial when dealing with forged documents or licences (Meinert et al., 2018).

4. Methodology

This section presents the methodology used to evidence the application of Blockchain technology for supporting BIM data provenance. The integration of Blockchain with BIM for data provenance uses a distributed network for storing provenance data over a decentralised and fault-tolerant ledger.

In this paper, it is combined two sources of evidence to deliver the paper objectives (i) secondary sources of evidence resulting from an in-depth literature survey exploring existing BIM-Blockchain solutions and subsequent integration for construction applications and (ii) primary sources of evidence from a real construction case study involving the construction of a highway bridge.

By extracting evidence from the literature survey complemented with requirements from the case study, a new Blockchain provenance framework was proposed to ensure reliable BIM data exchanges and collaboration across project disciplines. The objectives were primarily focused on developing a capability to support distributed BIM data sharing for construction projects based on a scalable and secured provenance model that can incentivise collaboration between stakeholders. The above objectives were achieved using the following methodological steps as shown in Fig. 1:

Phase 1: Requirements elicitation - an initial set of requirements have been collected from the project trial in order to understand and plan effective integration of Blockchain technology with BIM for data provenance. Data and evidence informing the decision for adoption of the provenance framework were collected from the client, participating disciplines and expertise from the consortium complemented with results from the literature survey.

Phase 2: Qualitative research - qualitative research data were obtained from a wide range of secondary sources, including research articles, case studies and best practices from the construction sector. This included an in-depth literature search using journal and conference articles, books, whitepapers, and reliable data sources. The review was aimed at discovering how Blockchain technology is being used in construction and other industries, with a special focus on case studies and industrial applications.

Phase 3: Data consolidation - following the completion of these analyses, the resulted information was consolidated and analysed to inform the development of BIM data provenance models and scenarios.

Phase 4: Experimental testbed - the experimental testbed has been configured with a Blockchain environment Remix Ethereum platform and Kovan testnet which is a public Ethereum test network to support the implementation of smart contracts.

Phase 5: Development of smart contracts - development of smart contracts, compilation and distribution processes based on scenarios on the Remix platform. Smart contracts have been adopted and implemented using Solidity to support various project provenance functions as identified in the scenarios.

Phase 6: User interface - a web page was constructed to enable a more intuitive Blockchain interaction with smart contracts.

Phase 7: Results - scenario results have been presented and interpreted to demonstrate the efficiency of the BIM-Blockchain integration for data provenance.

Using the above stages, it is demonstrated how Blockchain can be integrated with a BIM environment using an IFC model developed for a bridge highway project.

4.1. Blockchain-based data provenance

For analysis, data from the Clouds-for-Coordination project (Petri et al., 2017) is used, which aims to support inter-company collaboration through the exchange of BIM data. As BIM allows information sharing across the construction and property management sectors, the issue of data trust becomes important – a problem that is becoming more widely recognised in the AEC industry through the use of 'Issue Status' for physical documents. The project participants develop, maintain, and manage their own BIM data where each discipline can retrieve an aggregated BIM model combining replicas from the project discipline model version (Petri et al., 2017). Each action that occurs throughout the process of construction design is recorded utilising Blockchain with an unchangeable proof of work raising trust and transparency across project participants. Fig. 2 illustrates the process of recording provenance data to Blockchain within a BIM environment.

For establishing data provenance, each record is compiled and then published to the Blockchain network and shared across the network nodes. Each provenance input is given a Blockchain receipt for future validation purposes whereas the provenance records are connected with a hashed user ID to ensure that nodes in the Blockchain network provide the privacy of data records. The network operator has the ability to manage the datasets and the portfolio of users to ensure reliability (Ramachandran et al., 2017). A record of data provenance is broadcast globally, and each block is confirmed within a set of Blockchain nodes.

Fig. 3 illustrates the process of saving a project file or an action on Blockchain using smart contracts. Smart contracts are a form of computer protocols that enable the creation of contracts without the need for contractual intermediaries (Alliance, 2012). A smart contract specifies the number of attributes including address, functions, and status, and permits code execution (Bahga and Madisetti, 2016) for the project disciplines. The value of smart contract applications for construction projects is primarily related to the safety and accessibility of data blocks distributed in a peer-to-peer environment (Mohanta et al., 2018). As a result, the provenance model based on smart contracts is in the form of computer code-written agreements that are intended to be implemented to capture various circumstances and events taking place within the project disciplines (Alliance, 2012).

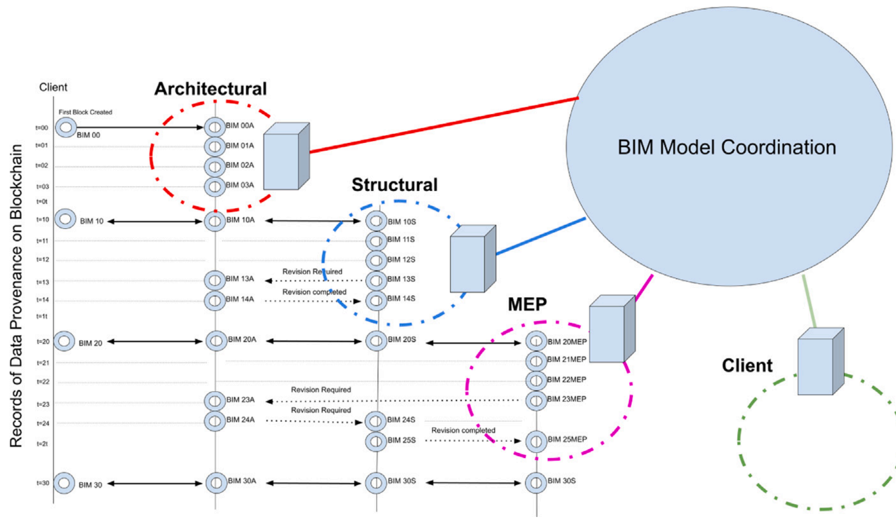


Fig. 2. Blockchain integration with BIM data.

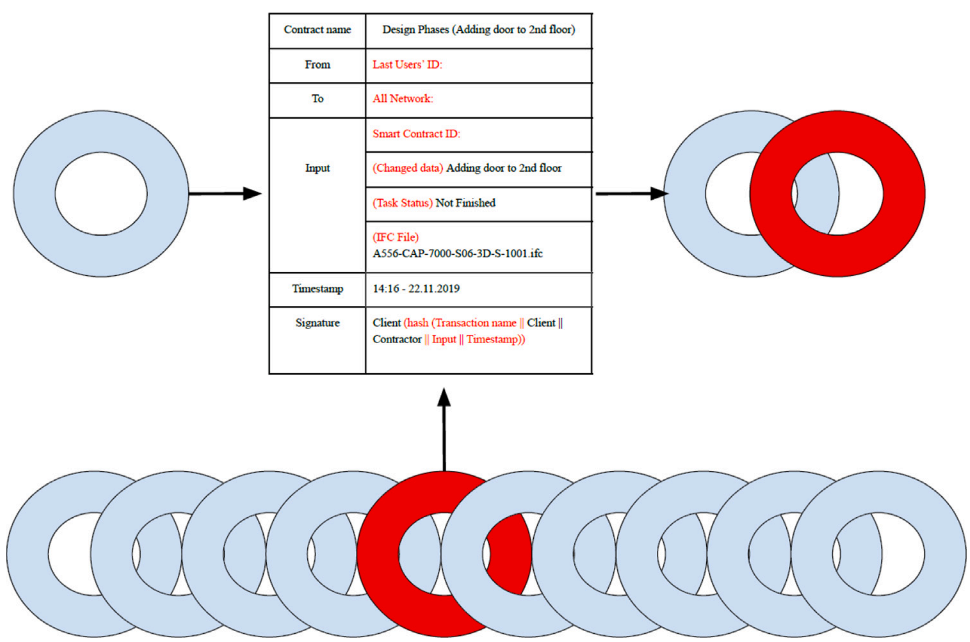


Fig. 3. An example of saving a construction project file or an activity on the Blockchain.

5. Case study description and BIM data model

Using the IFC model of a highway bridge to represent data within the project consortium and participating disciplines, data from the Clouds for Coordination project is used. The IFC model includes all bridge information, graphical and non-graphical information, throughout the entire project lifecycle, from planning to design, construction and use, and bridge operation (Honti and Erdelyi, 2018). The IFC model is composed of geometric and non-geometric data as shown in Fig. 4. The project data was reviewed, analysed, and changed in a variety of ways using software programmes and then exported to an IFC file to enable data transfer across applications. The IFC file format is based on an ISO standard (10303–21) referred to as the "STEP-file" (Grani, 2016).

For the scope of this research, the IFC schema is regarded as a storage system for storing and transferring digital data for interoperability amongst different BIM experts working on a particular project. IFC defines a detailed definition through various formats such as .ifc .ifcXML for ensuring hierarchically structured elements (Honti and Erdelyi, 2018; Isikdag, 2012). The *.ifcXML extension of the IFC file utilises the same data schema as the *.ifc extension, but it is displayed as an XML document rather than an ASCII file (Honti and Erdelyi, 2018). The IFC and ifcXML standards are both open and publicly available. IFCXML files utilise the same data structure as "traditional" IFC files, but instead of an ASCII representation that simplifies machine-to-machine data exchange (Isikdag, 2012).

5.1. Blockchain project network

The project involves multidisciplinary teams that collaborate to produce a consolidated BIM model from which provenance data is recorded into Blockchain. To ensure that the whole historical information is maintained in a tamper-proof way, the process needs a Blockchain trustworthy management and monitoring. The stakeholders involved in the project, Client, Architect, Structural Engineer and MEP, communicate and recorded their activities using smart contracts

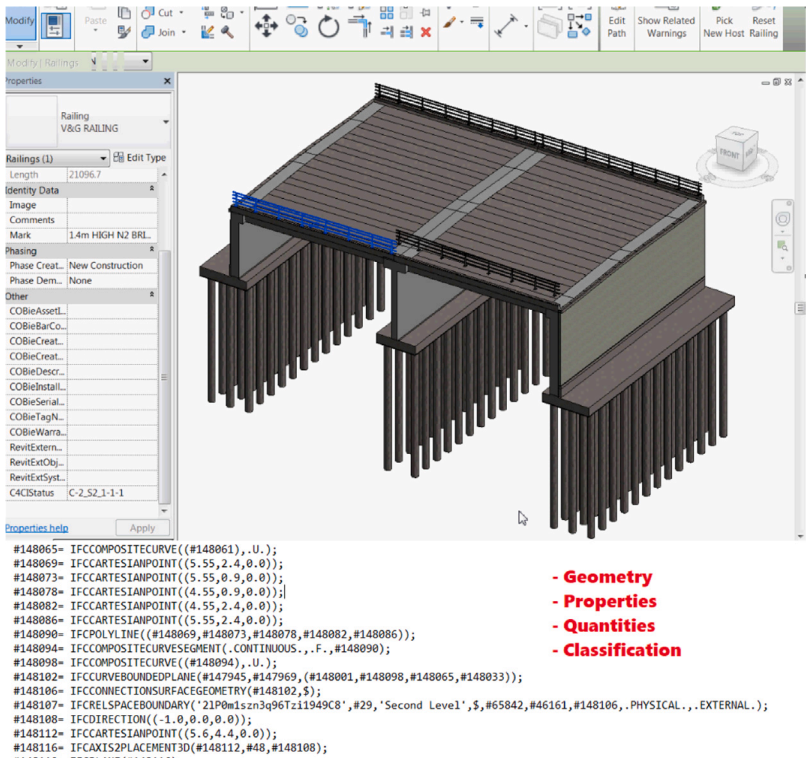


Fig. 4. Geometric and non-geometric BIM data of the trial project.

through a front-end layer (see Appendix). The front-end is a decentralised application that connects stakeholders to the smart contract through available interfaces using RestHTTP, Web3, or JSON RPC.

Blockchain smart contracts were designed to support the BIM data provenance regarding the interoperability requirements of the construction project. API calls are used to process IFC objects and related metadata in order to facilitate the use of a project's background by disciplines. This enables a distributed manipulation of these IFC objects in situations where multiple disciplines associated with a project can work on the same IFC model within the coordination system. The project partners use a Revit plugin that connects Revit software to the coordination framework, as well as a filtering application that chooses IFC objects according to their compliance codes. The Revit plugin communicates with the system to retrieve and send IFC objects based on discipline updates.

Blockchain registrations are performed based on an IFC model, along with methods for data transfer and data provenance across disciplines. This enables disciplines to obtain the most recent version of an IFC object in real-time and modify the IFC model appropriately recording each operation to Blockchain through data provenance. For the project network, Blockchain and cloud architecture are accessible through a user interface designed following technical and building industry standards. The user interface has been designed to accomplish two tasks: (i) an initial interfacing of the Blockchain with the C4C network, and (ii) continuous system administration (Petri et al., 2017). The basic procedure for constructing a network is shown in Fig. 5.

The following steps are identified in a Blockchain data provenance workflow from Client invitation to discipline operation and Blockchain registration:

- Step 1: Project Client (Client) configures the project and exposes the site URL to enable downloads of the BIM model.
- Step 2: To invite project disciplines to participate in an event, the client sends invites through email that includes a link to download the software, as well as an embedded IP address of the coordinator server.
- Step 3: The disciplines download the model and implement updates on the BIM model according to the project plan using IFC objects updates and operations.
- Step 6: Disciplines will be notified through email about the implemented updates on the BIM model according to a suitability matrix.
- Step 7: The resulted model metadata with corresponding BIM properties are stored in Blockchain after each discipline update in the form of a tuple as presented below.

```
struct contract[string operation, uint time, string
model, uint version, address objectID, string owner];
```

- Step 8: Using the Blockchain network, operations such as adding, deleting, and modifying smart contracts are undertaken using the front-end web page.

6. Evaluation

It is considered that a construction project involves a set of disciplines that collaborate to deliver project tasks. The evaluation is conducted using scenario data and models from the Clouds-for-Coordination (C4C) project, which involved multi-disciplinary collaboration for a highway construction project (Petri et al., 2015). The framework was developed across multiple disciplines involved in a real-world highway development project in the UK, which included the construction of a new bridge (Petri et al., 2017). Fig. 6 depicts the network architecture of the Blockchain-based BIM project environment.

Throughout the design phase of the bridge, the following part introduces a complete BIM model integration based on the Blockchain.

- Discipline A — Architect
- Discipline Aa — Architect assistant1
- Discipline Ab — Architect assistant2
- Discipline S — Structural Engineer
- Discipline C — Client

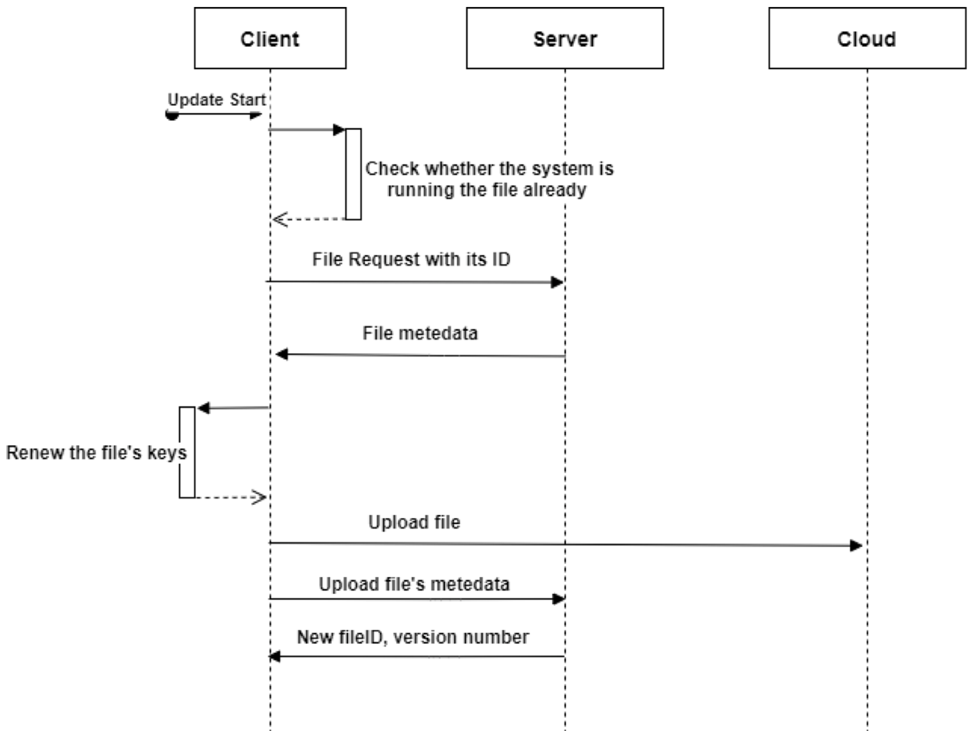


Fig. 5. Model update in the project network.

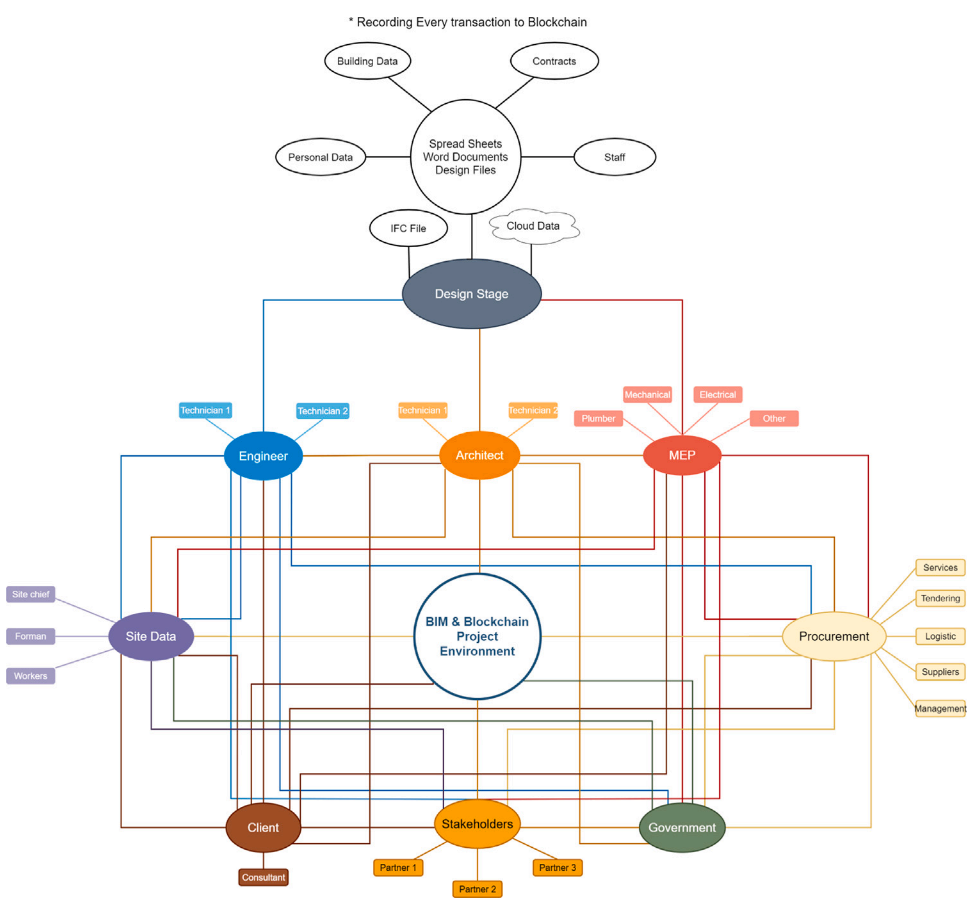


Fig. 6. Blockchain-based BIM Project Environment.

Table 1
Scenarios with input and output parameters.

Scenario	Recording blockchain general scenario	Discipline leaves the project
Objectives	• Disciplines register to Clockchain • Recording every change on the project 1. Change from IFC file 2. Action from the BIM environment (sharing data between disciplines)	• Recording every change on the project • Blocking leaving discipline access in the project Setting new smart contract and registering new discipline • Set and publish new due date on the project (to extend due date) • New discipline access to the project • The transaction that are recorded on the blockchain are generated by calling or involving a smart contract function. • If any of the verification or validation criteria fails, the function execution is reverted; however, if the execution succeeds, the generated action are broadcast to the network for recording.
Input parameters	• BIM model name-[ml.ifc] • Objects ID- [id1,id2,id3,… idp] • UderID-[id1,id2,id3]	• BIM model name-[ml.ifc] • Objects ID- [id1,id2,id3,… idp] • UderID-[id1,id2,id3]
Output parameters	• Discipline • BIM Model • Objects • Timestamp	• Discipline • Txt • BIM Model • Timestamp
Operations	getModel(),updateModel(),addUSer()	get-Model(),updateModel(),addUSer(),deleteUSer(),updateUSerProfile()
Action	• [Client]:Highway England • [Archetect]:Costain • [Engineer]:Capita • [A cost consult]:Lee Wakemans Ltd.	• [Client]:Highway England • [Archetect]:Costain • [New Engineer]:Capita

• Discipline M — MEP

Step 0 - “Discipline A”, “Discipline S”, “Discipline C” and “Discipline M” have been registered into the Blockchain system and get their unique Blockchain ID. All changes and activities which have been made to the BIM environment and the model will be recorded on the Blockchain. Each discipline “Discipline A” can have more users such as “Discipline Aa” and “Discipline Ab”.

Step 1 - Discipline C (Client): “Discipline C” has been created for the first block and proceeded with registering the first entity “Discipline A”. Discipline A will create the model ”Bridge BIM IFC file" on the Blockchain network. “Discipline A” will continue to record all design changes on the Blockchain system.

Step 2 - Discipline S (Structural Engineer): The created IFC file (A556-CAP-7000-S06-3D-S-1001.ifc) will be shared with the structural design team by “Discipline A”. The Blockchain is configured to keep consistent records on the network. “Discipline S” will start to analyse the architectural drawing and develop the structural design. The IFC file will be shared with “Discipline S” which will start working with the IFC document as a drawing structural design with changes to be recorded in the Blockchain network. During all of these stages, every step of the design and file share between design teams has been recorded into the Blockchain network.

Step 3 - Discipline C (Client): When “Discipline A” takes to the final design from “Discipline S”, “Discipline A” will share with the “Discipline M” (or “Discipline S” will share with the “Discipline M”). The final IFC file from “Discipline A” will be shared with “Discipline C” at the same time in order to monitor the task process and for monitoring any data transactions.

Step 4 – Discipline A(Architect): “Discipline C” wants to change the electrical box on the drawings at the end of the process using the IFC file. “Discipline C” will send the IFC file to “Discipline A”. “Discipline A” will send the file to “Discipline M”. “Discipline M” will change the box, and will send it to “Discipline A”, “Discipline A” will send it to “Discipline C”.

Table 1 includes scenarios used for evaluating the approach using smart contracts and Blockchain in a BIM environment, taking into account a design process undertaken by a Client, Architect, Engineer and related disciplines. By testing the new model, it has been attempted to demonstrate the efficiency of smart contracts for BIM data provenance. Input and output parameters are defined, and the operations and actors involved in the process are also specified for each scenario.

6.1. General assumptions involved in the design process

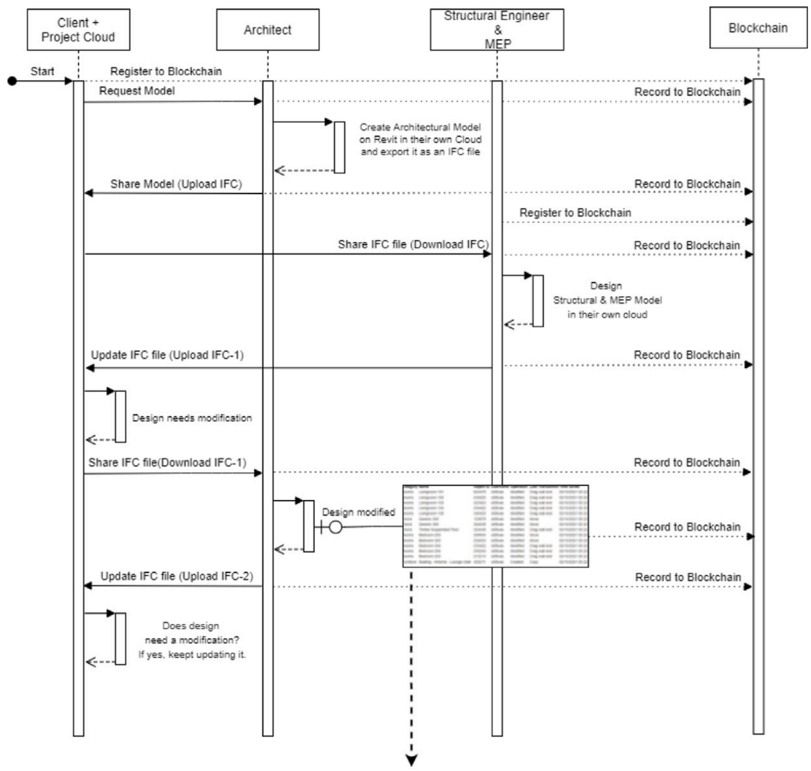
Considering a general project design process, the disciplines involved in the process are first recorded on the Blockchain and included in the process. After the registration process, the disciplines create their design and share the designs with the Client. Any information exchange or activity that occurs with the main “Project” will be recorded directly in the Blockchain system. Additionally, any changes to the IFC file will be stored in the Blockchain system as illustrated in Fig. 7.

6.2. Contracts

Remix platform is used to facilitate the compilation and deployment of smart contracts. Remix is an Ethereum Solidity development platform (Remix, 2022) that facilitates the development of smart contracts. Dapp (Musan et al., 2020) is another platform that was used to allow interaction with smart contracts through front-end web pages. In order to create the front-end web page’s interaction, a front-end JavaScript interface to connect the front-end page with the Blockchain system was constructed (Appendix A.1). The UI interface allows users to engage with contracts, including deploying new contracts and methods of the contract such as writing or retrieving Blockchain data. The Remix platform is used to deploy a single contract for system testing and the verification of the smart contract. For the testing phase, contracts and transmit transactions across the Kovantest network (Shakila and Sultana, 2021) were installed. Only on the developer device, local memory was invoked to quickly verify operations and provide execution results in real-time. Before deploying the smart contract on the Ethereum mainnet, its code was tested on a Kovan testnet (Anon, 2022). There are three smart contracts used to implement the Blockchain-based BIM provenance model for the case study presented in this study.

The smart contract for new user/actor/discipline registration:. It is considered that each contract is identified with the contract’s object number, which is maintained in a mapping connection to the updated contract address. The contract is created/updated for each discipline so that other nodes may see all the discipline records by using the `newUser()` function (see Appendix A.2).

The smart contract for object or input registration:. The contract serves as a means of registering objects and displaying all objects that have been registered. Once other nodes are registered to the platform, registered objects can be viewed through the platform using the `newObject()` and `Input()` functions (see Appendix A.3).



Category	Name	Object ID	Username	Operation	Last Transaction	Time Saved
Structural Column	Column 101	823479	si58vas	Modified	Drag column end	02/10/2021 00:22
Structural Column	Column 102	734223	si58vas	Modified	Drag column end	02/10/2021 00:22
Structural Column	Column 103	564422	si58vas	Modified	Drag column end	02/10/2021 00:22
Structural Column	Column 104	645433	si58vas	Modified	Drag column end	02/10/2021 00:22
Base	Span 1	324123	si58vas	Modified	Move	02/10/2021 00:23
Base	Span 2	321547	si58vas	Modified	Move	02/10/2021 00:23
Base	Girder 1	453265	si58vas	Created	Copy	02/10/2021 00:23

Fig. 7. The process of provenance records with design discipline.

Updating smart contract with users and actors:. The implementation of the object provenance model is performed via the first contract. After the disciplines are recorded on the Blockchain platform, every transaction should be recorded in the contract. With the `updateUser()` and `updateObject()` functions, the final User/Client may see the whole history of transactions for the object in use and may update the role of the users (see Appendix A.4).

Implementation Process:

- The smart contract was implemented using the Solidity programming language with the truffle infrastructure and a public blockchain designated Ganache system with truffle console was used to interact with the backend of the system. After the back-end server was built, the frontend website was developed and deployed to interact with the functions of the contract and to record the data provenance. The server-side code using Node.JS was implemented with a frontend interface that help to retrieve data provenance from the database rather than the blockchain. Contracts have been installed to allow users to utilise the system for data provenance activities.

Deployment Process:

- The Ethereum public Kovan test network with an existing blockchain Metamask wallet was used in order to deploy the experimental scenarios. Ganache was used to obtain ether for the purpose of testing an application and the address was broadcast on the Kovan testnet. The Solidity integrated development environment (IDE) and Remix are used to develop and deploy the smart contracts with a ruffle test to validate the existence of the address on the Kovan test network.

6.3. Authentication

All disciplines are registered into the network as illustrated in Fig. 8. The client then requests architectural drawings from the registered architect through the system. The architect shares the file with his design team. Because the hash code of the file will be uploaded to the Blockchain system, the file activities and provenance are recorded in a provenance database. Following that, the client requests the agreement to be validated using a Blockchain query to see whether the requirements of the smart contract are met. The authenticator verifies this process on the Blockchain and if the smart contract requirements are met, Blockchain verification generates a proof of data by updating the provenance data stored.

6.4. Verification

The BIM data associated with design elements are available in every version of the model chronologically, including where the project was used, who updated it, and when it was modified. This provides the capability to determine which data was requested and shared and whether it was approved. An immutable ledger will be accessed whenever an architect or member of any other discipline makes a modification or performs a task. Disciplines will be able to access object information over the Blockchain network by referencing the unique Object ID. This enables information to be accessible throughout the project's duration or at the end of the project. As input, the object's details may be retrieved by inputting the BIM Model ID, the Object ID, and, if requested, the discipline ID allowing access to historical records for the desired object over the Blockchain network. Several operations for a BIM object are considered for the verification process allowing the disciplines to:

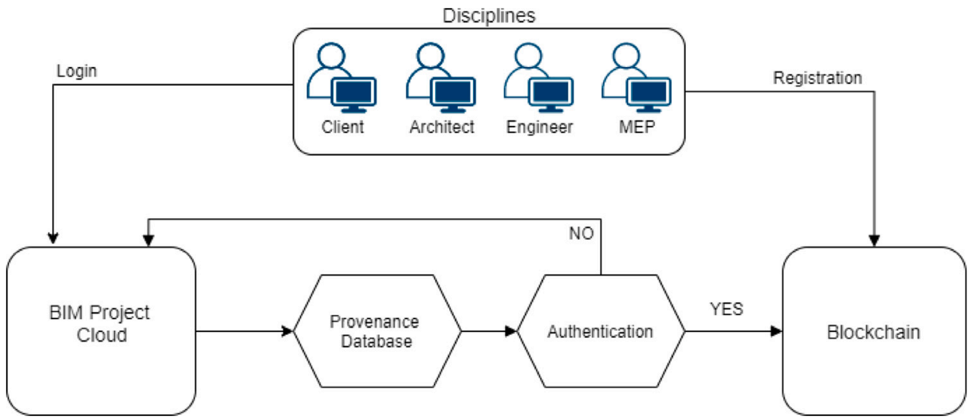


Fig. 8. The general structure of provenance record to Blockchain.

- to check the details about an object, operation and time.
- to access specific information on where an object is used in the process as well as the history of an object throughout the project's life cycle.
- to retrieve the details of an object that was manipulated by one of the disciplines throughout the project life cycle.

7. Experimental results

A prototype was implemented for the framework using an Ethereum Blockchain virtual machine, which provides a public Blockchain network. Ethereum uses a browser-based compiler called Remix-IDE for writing and compiling smart contracts. Solidity language has been applied for implementing the contracts.

Two smart contracts, named *provenance* and *verification*, are proposed for logging and verifying the information relevant to the disciplines, actors and objects. The former contract stores the discipline, objects, operations, time of actions, actors, and the versions of updates into a Blockchain network. The verification contract verifies: (i) the objects created/ manipulated by an actor; (ii) the operations of an actor on an object and the time of each operation of an actor on the object; (iii) the updated versions on an object which is modified by actors. The deployment costs of both smart contracts are investigated using an Ethereum public Blockchain test network (Kovan). The amount of gas used for deploying *provenance* and *verification* contracts are 854979 *wei* and 767248 *wei*, respectively. The transaction costs relevant to the proposed verification depend on the number of involved entities (e.g., objects, actors etc.) that should be investigated within a construction project. To this end, the functions/ transactions of the *verification* contract will be executed and evaluated costs according to various parameters.

7.1. Verification of operations

This experiment by changing the number of operations investigates the costs required for verifying the executed operation of an actor on an object and the exact time when the operation has been executed. The assumption is that the number of operations varies from 5 to 30.

The Kovan (PoA) testnet, which is a public testnet on the Ethereum Blockchain, was used for getting the transaction costs and mining time. Kovan is an Ethereum-based Proof of Authority (PoA) Blockchain that is publicly accessible. This testnet is the closest to the actual performance of the Ethereum Blockchain (Kovan, 2022).

Each result was calculated after five times executions of the transactions with different parameters to reach an average data. Table 2 gives the details about the average verification costs and mining time. As seen, when the number of operations increases, the amount of consumed gas increases steadily. In order to get the average mining time for the verification, the results with different gas price units ranging from 10 to 30 *Gwei* were evaluated. Given a fixed gas price unit, the verification costs in Ether (ETH) and mining time in seconds are provided.

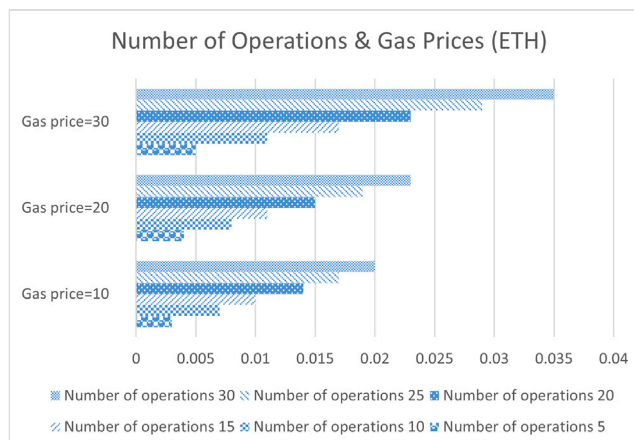


Fig. 9. Comparison of Number of Operations & Gas Prices (ETH).

Visualisation of the mining time with the different gas prices is shown in Figs. 9 and 10. The results indicate that the average mining time decreases sharply when the gas price unit increases. In fact, higher gas price motivates the miners to run the transactions and create the blocks sooner.

7.2. Verification of object's updates

This experiment verifies all the history of an object during the lifecycle of a project. The history shows all the updates of an object that has been modified by the actor(s). The experiment by changing the number of an object's updates from 5 to 30, estimates the amount of gas used for checking the object's history. It is assumed that the rate of gas price unit is 20 Gwei, being an average rate at the date of the experiment through Ethereum. The results have obtained after five times execution of transactions in Kovan with various parameters to get the average values. Table 3 shows the experimental results. The amount of gas consumption and the costs of the transactions in both wei

Table 2
Verifying operations and transaction costs.

Number of operations							Mining time
	5	10	15	20	25	30	–
Used gas (wei)	194235	388470	582615	776800	970125	1165410	–
Gas price=10	0.003	0.007	0.01	0.014	0.017	0.02	1477
Gas price=20	0.004	0.008	0.011	0.015	0.019	0.023	294
Gas price=30	0.005	0.011	0.017	0.023	0.029	0.035	25

Table 3
Verifying object's updates and transaction costs.

Number of updates	5	10	15	20	25	30
Used gas (wei)	48033	62100	78241	93004	103000	121050
Cost (ETH)	0.0021	0.0027	0.0032	0.0041	0.0044	0.0053

Table 4
Verifying actors and transaction costs.

Number of actors	5	10	15	20	25	30
Used gas	55251	105920	150680	201902	250032	291230
Cost (ETH)	0.0011	0.0021	0.003	0.004	0.005	0.0058

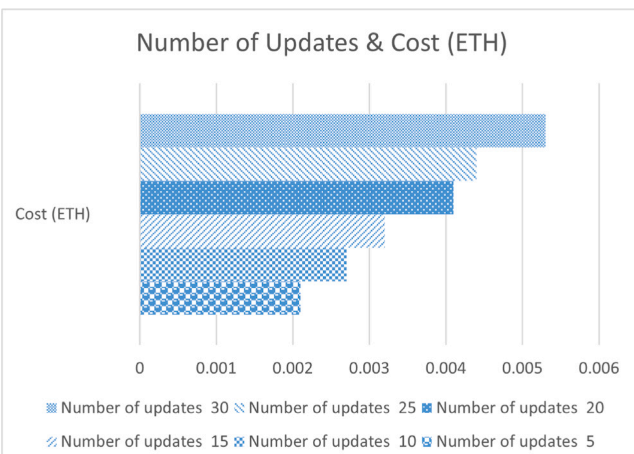


Fig. 10. Comparison of Number of Updates & Cost (ETH).

and ETH are, respectively, provided. As represented, when the number of updates over an object rises, the cost of checking the history of the object increases gradually. It starts from almost 0.002 ETH and reaches nearly 0.005 ETH.

7.3. Verification of actors

This experiment by changing the number of actors working on or manipulating an object investigates the costs required for retrieving the actors' details. The assumption is that the number of actors varies from 5 to 30. The gas price unit is 20 Gwei and the transactions are executed and deployed on the Kovan test network. The costs are calculated after five times of execution with various parameters to get the average results.

Table 4 shows the experimental results. As seen, when the number of actors increases, the gas consumed for the verification rises steadily. The table also provides the transaction costs of such verification in ETH. Fig. 11 and 12 show how gas fluctuates with the number of operations and updates identified in the smart contracts.

8. Lesson learned

This article demonstrates how to assure BIM data traceability and immutability via the use of Blockchain in the design process of developing a new bridge project. There are a limited number of applications on the subject of applying Blockchain to data provenance, despite the fact that the concept has been adopted and validated in several studies. Within the domain of data provenance, one research (Sigwart et al., 2020) estimates the cost of gas consumption affected with Blockchain, showing that the average latency converges to the average block timings of the various networks, since transactions with higher prices are virtually included in the next instant block. The study also compares the test networks Rinkeby and Ropsten demonstrating that the Ropsten testnet has more standard deviations compared to Rinkeby testnet. Another study (Ramachandran et al., 2017) proposed a monitoring system with contract executions on the Ropsten testnet network, demonstrating that the amount of gas needed per transaction for particular operations such as adding users or documents is almost consistent with the total amount of gas needed for each function. According to the reported findings, the majority of functional procedures may be performed at a relatively low cost.

This research demonstrates how a Blockchain-based BIM framework can be used for data provenance in construction projects. The work provides factual evidence from a real construction bridge project with smart contracts developed on the Kovan testnet network. The proposed provenance framework can accelerate the construction process across disciplines and facilitates reliable tracking and monitoring of project tasks while ensuring transparency. The results demonstrate that costs with the smart contracts implementing the provenance can fluctuate based on the number of disciplines and the size of the project. The research provides also valuable insights into the transformation of the supply chain management and realisation of digital construction which continues to be sought a topic of current interest in the field of study.

Traceable and immutable data transfer enable stakeholders to develop confidence in the data exchange and this assurance may aid in the utilisation of data obtained during construction for critical decision-making. The agreements, operations, and transactions associated with construction projects may be controlled by smart contracts when participants depend on project-related data. By gathering information between participants and supporting procedures and capabilities such as documentation, Blockchain with related BIM data provenance integration may contribute to more reliable source records. Given the fact that construction data is often gathered in a centralised source, it is necessary to preserve sensitive construction data using Blockchain's capacity to integrate a piece of data into the network ledger together based on an encrypted signature or private key.

It is argued that a smart contract has the potential to significantly accelerate the automating of the construction process. When established conditions are followed, a smart contract is automatically executed using computer code, effectively eliminating the requirement for trusted intermediaries for contracts. All project partners can agree on construction-related processes in the contract, and smart contracts automate tasks across disciplines. This procedure allows project partners to avoid project and operational delays that could lead to conflicts.

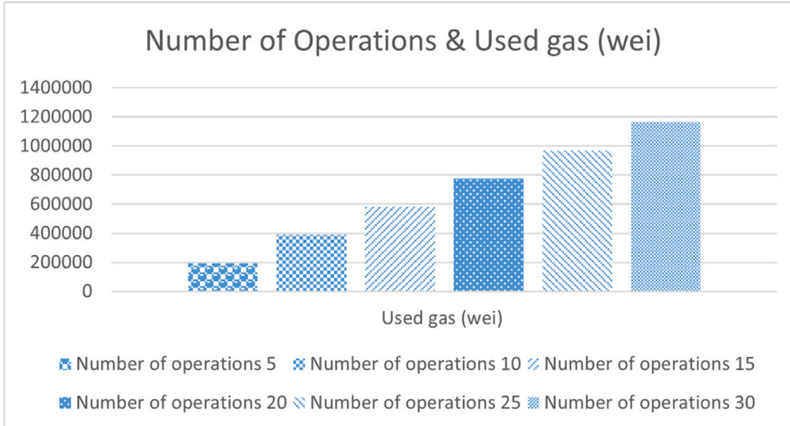


Fig. 11. Comparing Number of Operations & Used gas (wei).

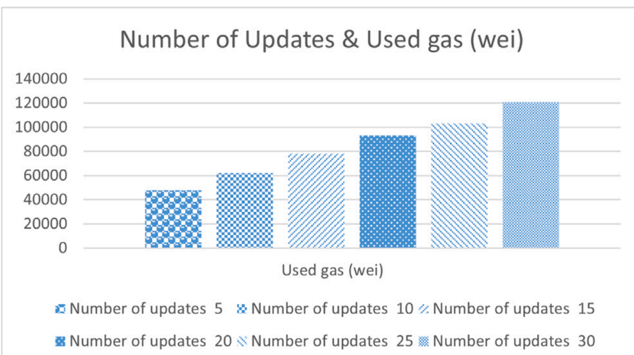


Fig. 12. Comparing Number of Updates & Used gas (wei).

The proposed work provides also valuable insights on the optimisation of the supply chain that can create various disputes and disagreements among players as a result of the contractual procedures. One of the primary causes of cost inefficiency or schedule delays in large construction projects is a shortage of the appropriate materials at the appropriate location and time. Such contract procedures may be governed by smart contracts in this context as Blockchain increases transparency and trust across all supply chains for off-site items. Exceptionally, if required, Blockchain technology can help to rationally reconstruct history precisely, thereby giving a major contribution to the traceability of operations and tasks for a construction project (see Appendix A.5).

9. Conclusion

A Blockchain-based BIM data provenance is proposed for construction projects that have the ability to record all activities and exchanges identified in a construction project. The work shows the steps required for the integration of a BIM data provenance model with Blockchain using construction data. The reported results are also evidence of how the number of disciplines and operations of a project influence total costs and gas with smart contracts.

This paper demonstrates how an integrated Blockchain architecture may aid securely traceable and immutable data interactions between project participants. Trust in project-related data may be established via traceable and immutable data exchanges. Data provenance may substantially accelerate future contract implementation, operations, transactions and evaluation, facilitating better communication across project participants while incentivising cooperation and collaboration.

A Blockchain data provenance can support real-time monitoring of discipline activities as evidenced by the real construction case study provided in this paper. It is projected that collecting data utilising provenance data with Blockchain while documenting the BIM project life cycle, can benefit the construction sector in a variety of ways. To begin, by documenting all aspects of the project throughout the BIM process, any data loss can be prevented, since the whole record will be permanently registered to the Blockchain system. Secondly, with the smart contract advantage, redundant documentation generated throughout the BIM process will be eliminated, and the process will be digitally documented in a Blockchain environment. As a result, it will aid in the acceleration of construction data processing and can reduce redundant and excessive document workload. On the other side, it is expected that a transparent approach would promote confidence among construction stakeholders. This can increase transparency throughout the process and promote communication between stakeholders.

With multidisciplinary construction projects, the availability and persistence of date records are essential. By adopting the proposed approach, the records of the drawings can be made available as data provenance using Blockchain enables the reconstruction of activities in accordance with the project tasks. It has also demonstrated that costs affected by data provenance can vary in direct proportion to the number of disciplines involved in the process and the volume of data recorded.

As a future work, Blockchain scalability and performance as well as its integration into the construction sector should be analysed and optimised by taking into consideration particular scenarios and events identified in construction projects. Also, integration with existing digital infrastructures such as smart IoT-enabled devices, and cloud interactions should be improved and harmonised in order to boost the usage of Blockchain in the construction sector.

CRediT authorship contribution statement

Yasin Celik: Definition, Formal analysis, Writing – original draft, Software, Data curation, Methodology, Validation. **Ioan Petri:** Conceptualisation, Writing – review & editing, Supervision, Methodology, Validation, Project administration. **Masoud Barati:** Software, Resources, Data curation, Investigation, Validation, Writing-Editing.

Declaration of competing interest

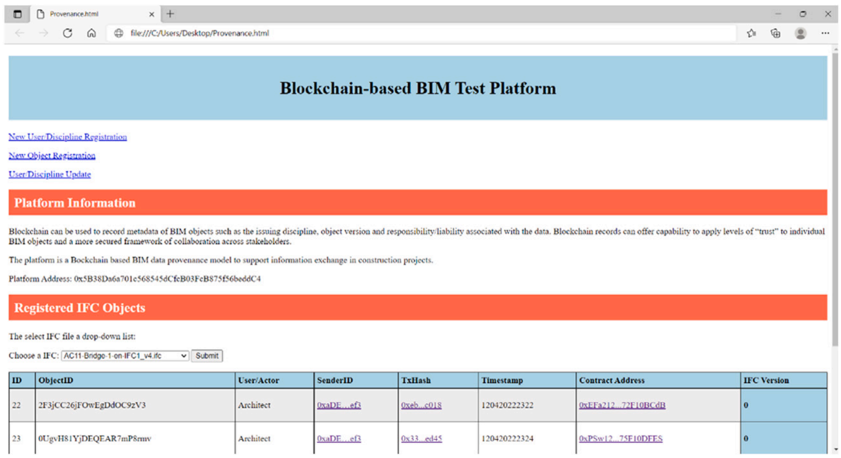
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors would like to acknowledge support from the Clouds-for-Coordination (C4C) project in terms of access to project trial data.

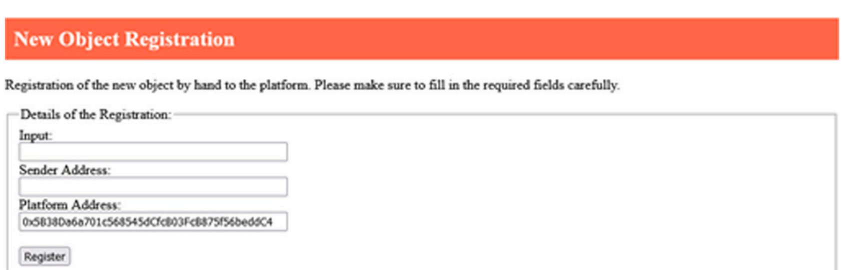
Appendix

A.1. Main page and general information of the platform

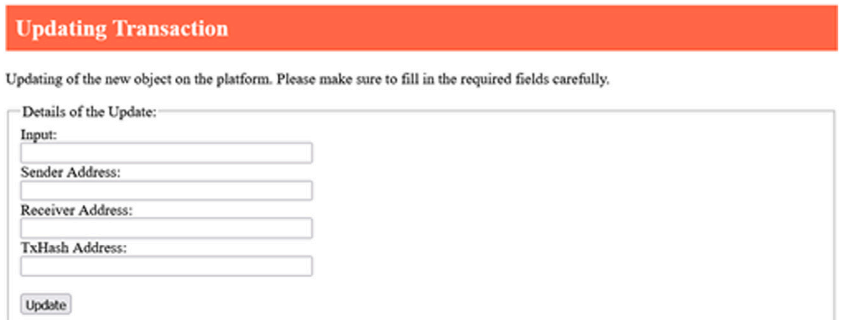


A.2. New discipline registration

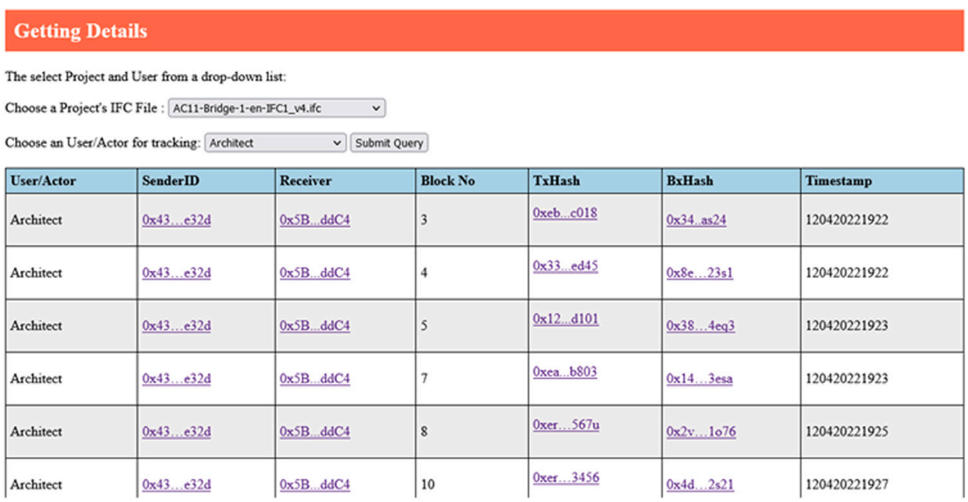
A.3. New object or input registration



A.4. Updating transaction



A.5. Visualising model transactions


Getting Details

The select Project and User from a drop-down list:

Choose a Project's IFC File : AC11-Bridge-1-en-IFC1_v4.ifc

Choose an User/Actor for tracking: Architect Submit Query

User/Actor	SenderID	Receiver	Block No	TxHash	BxHash	Timestamp
Architect	0x43…e32d	0x5B…ddC4	3	0xeb…c018	0x34..as24	120420221922
Architect	0x43…e32d	0x5B…ddC4	4	0x33…ed45	0x8e…23s1	120420221922
Architect	0x43…e32d	0x5B…ddC4	5	0x12…d101	0x38…4eq3	120420221923
Architect	0x43…e32d	0x5B…ddC4	7	0xea…b803	0x14…3esa	120420221923
Architect	0x43…e32d	0x5B…ddC4	8	0xer…567u	0x2v…1o76	120420221925
Architect	0x43…e32d	0x5B…ddC4	10	0xer…3456	0x4d…2s21	120420221927

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