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Integrating BIM and Blockchain across construction lifecycle and supply chains

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ABSTRACT

The Construction industry has a complex structure with multiple parties involved, which often leads to "adversarial relationships", "risk avoidance", and a "lack of trust" among the different actors. This culture is further compounded by a "linear workflow" that often results in low efficiency, delays, rework and unnecessary waste. Blockchain technology can help to mitigate these issues by creating a decentralised and transparent system, where all the actors can have access to a shared database, it allows tracking and monitors the different stages of the project, and even automate some processes increasing efficiency and reducing delays and rework.

This study highlights the advantages of Blockchain technology, particularly how it can provide a single source of truth for project data while allowing multiple parties to access and share data in a secure and transparent way, improving the workflow of BIM projects and decreasing the likelihood of errors, mistakes, or fraudulent activities. The paper explores the integration of BIM and Blockchain across life cycle and supply chains based on the RIBA plan of work, with the objective to streamline collaboration while improving process efficiency and resource traceability in projects. The study proposes a roadmap performing a detailed literature survey for Blockchain adoption in the construction industry, and validated on a real-world Bridge project. Furthermore, this study is innovative since it examines the integration of BIM and Blockchain throughout the entire project lifecycle by simulating the smart contract implementation based on the RIBA plan of work, thus providing an in-depth examination of the potential benefits of this integration.

1. Introduction

The construction industry is known for its complex information environment, siloed workflows, and lack of coordination between multiple stakeholders. This resulted in a blaming culture and repeated legal disputes. With the use of Building Information Modelling (BIM), there has been a trend toward increased coordination and integration of data from several fields. BIM facilitates effective data management and communication, eliminating traditional barriers and enhancing project outcomes (Ho and Liu, 2004). Data and information come in various formats, and are generated and maintained by different groups of users and communities, including local organisations and government authorities. Coordinating the sharing of this data across different disciplines such as architecture, structural engineering etc. for project tasks can be challenging, as it requires overcoming the difficulties of interoperating and integrating diverse and distributed resources (Petri et al., 2014).

The integration of BIM into the construction industry has significantly enhanced the planning to recycling stages of a building's life cycle. By offering a centralised, consistent, and reliable source of information, BIM facilitates optimum collaboration and knowledge exchange among all stakeholders across all disciplines (Krämer and Besenyői, 2018). This increases the accessibility of project data for numerous reasons, including design, data management, simulation, and activity scheduling (Keskin et al., 2021). Digital construction, which incorporates a variety of technologies, builds on BIM to provide even more sophisticated capabilities across the whole project life cycle (Vinayak et al., 2018). From automation of fabrication to comprehensive data analysis, digital construction provides better decision-making, especially in large, complicated infrastructure projects with many variables (Koseoglu et al., 2019). Coordination between different project teams and stakeholders is one example of a variable that digital construction may assist with. Multiple design teams and contractors and subcontractors may be responsible for various stages of construction on a large-scale infrastructure project. By using a digital platform that enables all project teams to access and interact on the same set of data, construction professionals may better coordinate their work and eliminate mistakes and delays caused by misunderstanding (Nikologianni et al., 2022).

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While BIM promotes digital collaboration, information sharing, and data management, it falls short in supporting updates or tampering with digital records, including changing the date, time, or other metadata operations within the BIM model. This is because, BIM software is primarily built with the focus of managing and visualising information related to the building design, construction and management, which includes 3D models, 2D drawings, and non-graphical data (meta-data) of the building elements, such as material properties, energy consumption, etc. However, the main focus is not to guarantee the integrity of the information or be able to track changes in the information over time. Therefore, although BIM tools allow users to make changes to project information, they may not include advanced security features or tamper-proofing mechanisms that are required to protect the integrity of digital records and guarantee the authenticity of the data. Additionally, BIM software usually does not have a version control mechanism to track the changes made to the project information over time. This could make it difficult to determine who made a change, when it was made, and what the change was if the integrity of the information needs to be reviewed. Blockchain has the potential to complement BIM by mitigating risks related to the lack of information traceability, thus providing a higher authority to paper-based records, while ensuring integrity, security of transactions, and trust (Chynoweth et al., 2007). Information that engineers produce for projects, such as specification documents or case studies, can be embedded into smart contracts. Individual pieces of engineering information would become commoditised, allowing external collaborators, such as clients, to quickly and easily access their specific information needs. This improvement can open up a plethora of possibilities in terms of fee structures and the potential for engineers to gain additional rewards for their essential contribution to projects and society (Nawari and Ravindran, 2019a).

The aim of this research is to investigate the benefits of using Blockchain technology in BIM activities in the construction industry. The primary objective is to enhance collaboration, process efficiency, and resource traceability by establishing a single source of truth for project data and enabling different stakeholders to securely access and share data. Based on the RIBA work plan, this is achieved by integrating BIM and Blockchain throughout the whole project life cycle and supplier chains. This study is relevant to the construction industry since it addresses issues such as errors, mistakes, and fraudulent activities that might arise throughout the construction process. By implementing Blockchain technology, the research intends to minimise these challenges and enhance the entire project's efficiency. Moreover, the research contributes to the body of knowledge by proposing a road map for Blockchain adoption in the construction industry and validating it on a real-world bridge project. In addition, by simulating the deployment of smart contracts based on the RIBA plan of work, the study provides an in-depth evaluation of the possible advantages of integrating BIM and Blockchain throughout the entire project lifecycle, which is a novel and innovative aspect of the research.

Following this introduction, Section 2 provides a review of related work. Section 3 presents the methodology utilised to undertake our research followed by Section 4 that provides an extensive set of analyses and applications for Blockchain and BIM for construction lifecycles. Section 5 validates our work in the context of a real-trial case study where Blockchain and BIM are utilised to deliver a multi-disciplinary construction project and presents the results analysis and implications. Section 6 concludes the paper and provides perspectives for future work.

2. Methodology

Blockchain is a developing technology with applications for multiple disciplines such as cryptography, computer science, finance and politics. As such, several industries, including the construction industry, are increasingly developing applications and case studies to address the ongoing digitalisation process. The paper addresses the following research questions: (RQ1): What is the application and level of integration of Blockchain and BIM in the construction industry? and (RQ2): Can the integration of BIM and Blockchain offer a lifecycle and supply chain approach to address construction industry limitations and blockers? Given the limited availability of experts, it was deemed difficult to gather primary sources of data through interviews, questionnaire surveys or other means. Hence, a qualitative approach based on secondary sources of evidence was adopted. This includes publications, case studies, reports, and white papers from a wide range of industries. The methodology involved the following steps:

- A comprehensive literature review was performed using academic and conference papers, textbooks, technical documentation and authoritative Internet resources to understand existing state-of-the-art Blockchain applications in the construction industry. A comprehensive literature search using authoritative databases such as Science Direct, Scopus and Google Scholar was conducted. Each article raises has helped elicit the level of awareness, maturity, and capability in the implementation of Blockchain and smart contracts in the construction industry.
- The portfolio of authoritative resources was analysed to determine how Blockchain and BIM are used in various industries based on different application requirements. Literature and published expert comments were analysed critically to identify common issues in the construction industry.
- A real construction project model integrating BIM and Blockchain has been applied for a new bridge project to validate our research hypothesis. The trial shows how BIM and Blockchain can support data and document sharing between stakeholders.

The proposed model for Blockchain integration with BIM is illustrated with corresponding critical insights in Fig. 1. In construction projects, managers coordinate project activities depending on the project's complexity and existing resources. Recently, project activities have begun to change due to the emergence of BIM where a BIM manager is involved in all phases of the project and can manage the project on behalf of the Client. In the proposed structure, the Client and the BIM manager is presented as leading user of Blockchain.

3. Related work

The research we conduct is performed primarily from the review articles related to the adoption of Blockchain in the construction industry and its subsequent integration with BIM. The typical findings of the analysed articles reflect technology's contribution to the market, its necessity and the general features of Blockchain technology for construction projects. We validate these research findings in a real construction project using BIM data models from Highways England involving the construction of a new bridge.

We have adopted a mixed methods approach that combines primary sources of evidence from a real construction project and secondary sources of evidence as reported in research studies. We have analysed research taking into account the existing studies, reports and best-practice case studies. The keywords for undertaking our literature survey were "BIM" AND "Blockchain", "Blockchain in construction" and "Smart contracts in construction".

The literature survey shows that quite a few papers review Blockchain and subsequent applications in the construction industry (Hijazi et al., 2019; Turk and Klinc, 2017; Ganter and Lützkendorf, 2019; Figueiredo et al., 2022a) as by presenting a system that facilitates financial transactions using smart contracts by coding the costs charged, benefits, and cost savings of IPD projects (Elghaish et al., 2020). The solution, which is built on Hyperledger Fabric, is designed and proposed to address challenges such as data security and authorisation management in the use of central BIM work processes (Nawari and Ravindran, 2019a,b). The other researchers used a simulated setup activity to validate the conceptual relationships provided (Li et al., 2019b) in

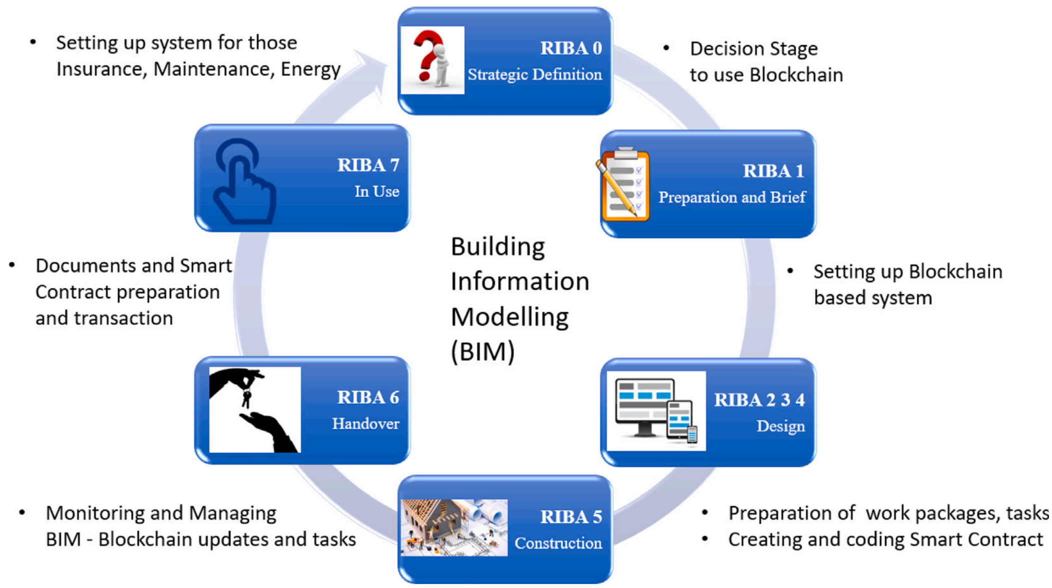

Fig. 1. Blockchain steps with BIM for construction lifecycle.

the proposed framework, which incorporates emerging information technologies such as cybersecurity and Blockchain characteristics into a typical university BIM curriculum (Hammi and Bouras, 2018). Additionally, one research investigates the potential cost savings of a real estate firm adopting Blockchain (Dakhli et al., 2019) and proposes a multidimensional structure for the implementation of DLT in the construction industry (Anon, 2019). Moreover, an article demonstrates the emergence of Blockchain by highlighting the adoption and progress of construction firms utilising this technology (Graham and Hailer, 2019), examining the conceptual basis for the design of an automated payment system, and evaluating the role of smart contracts in enabling cash flow to be efficiently and autonomously conditioned on the status of product flow (Hamledari and Fischer, 2020).

One study introduced several techniques and frameworks for implementing smart contracts with BIM in the construction industry (Mason, 2019), and the rest of them include semantic differential transaction (SDT) technique (Xue and Lu, 2020), Hyperledger fabric-based Blockchain network (Shojaei et al., 2019), a conceptual framework for a Blockchain-based design process (Srećković et al., 2021), a system for the autonomous management of building progress payments (Hamledari and Fischer, 2021), a framework for decentralised architectural design (Dounas et al., 2020), and a distributed common data environment (DCDE) architecture for BIM-based design and Interplanetary File System (IPFS) (Tao et al., 2021).

Implementation of Blockchain technology in the construction industry has shown that it has the ability to enhance the end-to-end design and construction process's process efficiency (Anon, 2023a) and data flow (Belle, 2017). Blockchain's primary advantage is its ability to provide an advanced solution to the problem of trust by providing a permanent (Kuperberg and Geipel, 2021), immutable (Elbashbishy et al., 2022), and reliable (Das et al., 2021) network that is capable of removing intermediaries (Heiskanen, 2017) and automating processes due to its prominent decentralisation (Kang et al., 2022), accountability (Cheng et al., 2021), and consistency characteristics (Xu et al., 2022). Researchers have also discovered that by connecting the BIM work process with Blockchain, change tracking (Figueiredo et al., 2022b) and data ownership (Nanayakkara et al., 2019) may be provided. In addition, the literature research has revealed that Blockchain can execute and release transactions when conditions are met (Hijazi et al., 2021; Mahmudnia et al., 2022), and encourage a decentralised collaborative building environment (Perera et al., 2020) increasing both the level of traceability (Li et al., 2019a) and the monitoring (Liu et al., 2023) and management in real-time (San et al., 2019; Anon, 2023b). It also found that it can overcome file redundancy (Erri Pradeep et al., 2021) challenges by creating a secure file storage system to ensure accountability (Ni et al., 2021), transparency (Shojaei, 2019), and trust (Rodrigo et al., 2018) by providing a single source of truth (Erri Pradeep et al., 2019).

Several shortcomings have been highlighted in the literature about the adoption of Blockchain technology in the construction industry. Technical challenges (El Khatib et al., 2022), lack of standards (Prewett et al., 2020), limited scalability (Chauhan and Patel, 2022), limited implementation (Gurtu and Johny, 2019), operational requirements (Cole et al., 2019), and the complexity of the technology (Berryhill et al., 2018) are among the primary limitations. The lack of standardisation (Lohmer and Lasch, 2020) in the use of Blockchain technology makes it difficult to compare and evaluate the efficiency of various implementations. Concerning the limited implementation of Blockchain technology (Andrian et al., 2018), many organisations are still hesitant to use it owing to a lack of knowledge of the implementation process and procedures (Li et al., 2022; Rejeb et al., 2022), and perceived risks (Drljevic et al., 2020).

Despite the general knowledge of the Blockchain, many companies still have not yet been able to find ways to integrate it into the business thoroughly. Businesses show particular interest in Blockchain, but the actual adoption is delayed. Gartner estimates that Blockchain will generate more than 3 trillion dollars in annual commercial value by 2030 while 10% to 20% of the global economic infrastructure will operate in Blockchain-based systems by 2030 (Panetta, 2019). Niya et al. (2018) have argued that peer-to-peer buying and leasing smart contract-based applications can meet the functional and legal requirements of automatic purchases and lease agreements using Ethereum on Blockchain. In this paper, we demonstrate that Blockchain can support also the development of applications in the design and construction of BIM workflows and contributes to the monitoring and recording of design and construction events with a view to facilitating Blockchain-based transactions for multi-disciplinary construction projects.

The literature survey has also reported several limitations around the adoption of Blockchain for construction case studies. From an environmental impact perspective, there are well-known Blockchain systems such as Bitcoin that use enough energy to power over 1.3 million households. Energy consumption ranges from that of a small power plant at a capacity of 10MW up to 3-6GW which embeds a certain risk

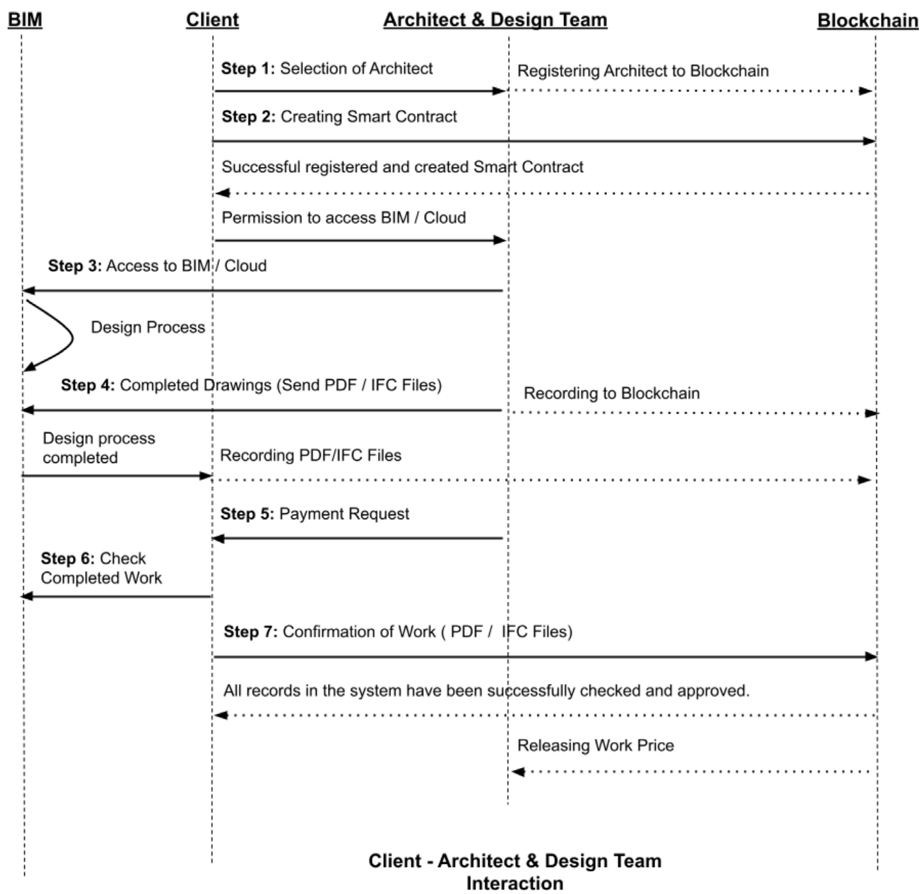

Fig. 2. Blockchain structure between Client and Design Team.

around environmental compliance and sustainability (Vranken, 2017; Nawari and Ravindran, 2019a; Ramachandran and Krishnamachari, 2018). As a novel technology, regulations cannot keep up with technological advances, it is expected that establishing adequate standards and policies will take a long time to reach its maturity, (Nawari and Ravindran, 2019a). In terms of scalability and privacy of Blockchain systems, all parties have the right to download the ledger which means that everyone has the right to see the full history of documented transactions, especially in a permissionless Blockchain architecture which can incur risks related to privacy breach (Nawari and Ravindran, 2019a; Singh et al., 2020; Zou et al., 2019).

The purpose of this research is to investigate the benefits of using blockchain technology in Building Information Modelling (BIM) activities in the construction industry. The primary objective is to enhance collaboration, process efficiency, and resource traceability by establishing a single source of truth for project data and enabling different stakeholders to securely access and share data. Based on the RIBA work plan, this is achieved by integrating BIM and blockchain throughout the whole project life cycle and supplier chains. This study is relevant to the construction industry since it addresses issues such as errors, mistakes, and fraudulent activities that might arise throughout the construction process. By implementing blockchain technology, the research intends to minimise these challenges and enhance the entire project's efficiency. Moreover, the research contributes to the body of knowledge by proposing a road map for blockchain adoption in the construction industry and validating it on a real-world bridge project. In addition, by simulating the deployment of smart contracts based on the RIBA plan of work, the study provides an in-depth evaluation of the possible advantages of integrating BIM and blockchain throughout the entire project lifecycle, which is a novel and innovative aspect of the research.

4. Blockchain for construction lifecycle

In this section, we explore Blockchain applications for construction life cycles with a view to supporting BIM adoption and achieving a higher order of digitalisation in the construction industry.

4.1. RIBA (0) strategic definition

The "definition" stage identifies a central step in the overall life cycle process, as it is necessary to question the necessity and usability of a construction project and therefore validates the use of Blockchain technology. This stage is the preliminary evaluation for determining when Blockchain is necessary for a construction project. In this case, a project is evaluated and identified before a detailed summary is formed, whether it is strategically appropriate to use Blockchain in a project while considering setting up the project team.

4.2. RIBA (1) preparation

Project summary and related feasibility studies of a construction project will be developed and completed in the preparation stage. Pre-implementation meetings may also be required to test the accuracy of the strategic summary. To assess whether Blockchain technology is required for a project, a roadmap covering the roles and responsibilities needs to be prepared for each discipline involved in the project. Furthermore, the duties and responsibilities of the disciplines to manage the information exchange are determined at this stage.

In this stage, a project risk assessment is required to identify risks for each discipline. The development of the procurement strategy, the project program, and in some cases, a (city) planning strategy is part of this initial risk analysis (Sinclair, 2013).

4.3. RIBA (2,3,4) design stage

The design stage is an information stage that includes conceptual designs, schematic designs, detailed designs and contract documents. This information is transferred from designers to Contractors and to Client. Blockchain can be used in this stage as a distributed network that can establish a reliable connection for sharing files between customers, contractors and other stakeholders. A shared design can be stored on a Blockchain network with an associated chain to provide transparent and faster payments through smart contracts. During the planning phase of the project, various design packages need to be defined. Moreover, services are applied to smart contracts as a mean to execute payments according to the business plan and to deliver on the project activities in a timely manner (Penzes, 2018).

The proposed structure of the Blockchain can apply in a similar track from the beginning to the final stage of the building process. This structure contributes to an understanding of Blockchain and its current state of the art technology and the use of financial and data sharing mechanisms throughout the construction process. Blockchain and BIM integration can also lead to significant savings, taking into account transaction fees, paperwork, and construction permits, and removing third parties.

Fig. 2 presents the interaction between different disciplines in the design phase as supported by a Blockchain system identifying the following steps:

- *Step 1:* An agreement is signed with an appropriate architect who will continue to contribute to the project.
  Step 2: The Client and the Architect will send their digital information such as digital address and hash to create a smart contract. When the smart contract is prepared, the registration process will be submitted to the Blockchain network.
  Step 3: The Architect will get permission to access BIM/Cloud system and contribute with the designs to the project.
  Step 4: The first draft of the project will be prepared by the Architect and will be sent to the Client. The Client will check the draft and will give feedback regarding project requirements. Then the Architect will produce the design based on the received feedback. When the entire design is finished, the Architect will save the model in a BIM format and will send the final IFC file to the Client.
  Step 5: In this step, the Architect can request payment after making sure all drawings are completed.
  Step 6: The payment will be submitted by the Client in order to check drawings. If there is no need for another round of feedback which means the architectural design is completed, the Client will approve and sign it, and the process will be completed.
  Step 7: The Client will send the drawing files as a PDF/ IFC to the Blockchain network to build an immutable data history record. The smart contract may send a notification to both parties, and the Architect's service price will be paid, and the transaction will be recorded to Blockchain.

- The same processes will be followed for Structural, MEP, and other design team participants.

All these interactions are registered on the same Blockchain network, so payments and project performance measurement updates can then be started with smart contracts. This process is very similar to those found on construction sites today. However, since there is an underlying automatic and unchanging layer of Blockchain, each sequence of tasks is recorded and tracked by the corresponding payments in the field for approval and job completion. In this way, payments can be processed from the project account and a transparent flow of value can be created at the bottom of the supply chain.

At this stage, the BIM work package includes the dates, quantity and costs of the work for Contractor and Subcontractors to use in the construction process as shown in Fig. 3. A BIM work package can be created with software such as Synchro and Costx, considering the transaction date and cost. These packages divide the construction process into small pieces of digital use while recruitment, job tracking, and payments can be easy to follow.

4.3.1. Smart contract

The translation between a traditional contract and a smart contract with subsequent transformation details is presented in Fig. 4. This shows an overview of how smart contracts operate in a Blockchain and identifies: (i) terms and conditions specification, (ii) coding under the determined condition in Blockchain, (iii) conditions are met and the smart contract executes itself, (iv) outcomes are recorded in the Blockchain and (v) authorities and users can analyse events.

In order to create a smart contract, the parties must first define the corresponding objectives for each party and agree on the expected outcomes. This may involve any potential value exchange, including goods or services. Collaboration parties (disciplines) will adjust the parameters and requirements that must be met in order for a transaction to occur.

All specifications and contract clauses are then written with computer logic and coded in a programmatic way. Then the smart contract will be sent to the Blockchain, that will be executed on its own when specific criteria are activated. Users must use external owner accounts to launch a smart contract to perform a transaction with a contract account. This account is authenticated with the private key of the initiator and forwarded in the Blockchain to other nodes. Other users may use the created public key to verify the validity of the transaction to ensure the initiator is the entity that has activated the transaction (Iansit and Lakhani, 2019).

When a consensus is achieved from the majority, the transaction will be added to the ledger, the smart contract will be executed, and the results will be registered. As the Blockchain status changes overtime, it is modified on all network nodes, and the outcomes cannot be altered. Due to the computational resources needed to manage the proof of business framework, any transaction that causes a change of status in the Ethereum Blockchain requires a transaction fee. The transaction launcher pays in Ethers which are part of Ethereum's local value network.

4.4. RIBA (5) construction

The use of smart contracts for the construction stage aims to manage and monitor changes in the design and construction phases of the BIM model, and to keep a record of all changes in the model by effectively monitoring standard permits and legal residences (Lohry and Bodell, 2015).

The same Blockchain structure as used in the design phase can be used for the construction phase. In this phase, the difference is that the Contractor will make the management of the Subcontractor.

Fig. 5 shows how to record IFC data with Blockchain across disciplines in order to process work packages and work payments. A suitable Contractor should be found/hired, and a smart contract will be developed between the Client and the Contractor in relation to the construction project. The Contractor will get permission to access the BIM model after providing the necessary information. The first work package will be sent to the Contractor and if the Contractor completed the package within the specified time, a smart contract will be executed. However, if the Contractor requests a payment to the Client without completing the smart contract requirements, BIM updates and the construction site verification are required to check the package status, and the Client can define the package status and the cost (can be sight from Cost Consultancy or others) for confirmation of the requested transaction from Contractor. When the confirmation of the work package status is received, the Client will agree with the amount, and the Contractor service price will be released. Subsequent transactions, the package files and the updated BIM IFC files will be recorded into the Blockchain as illustrated in Fig. 5.

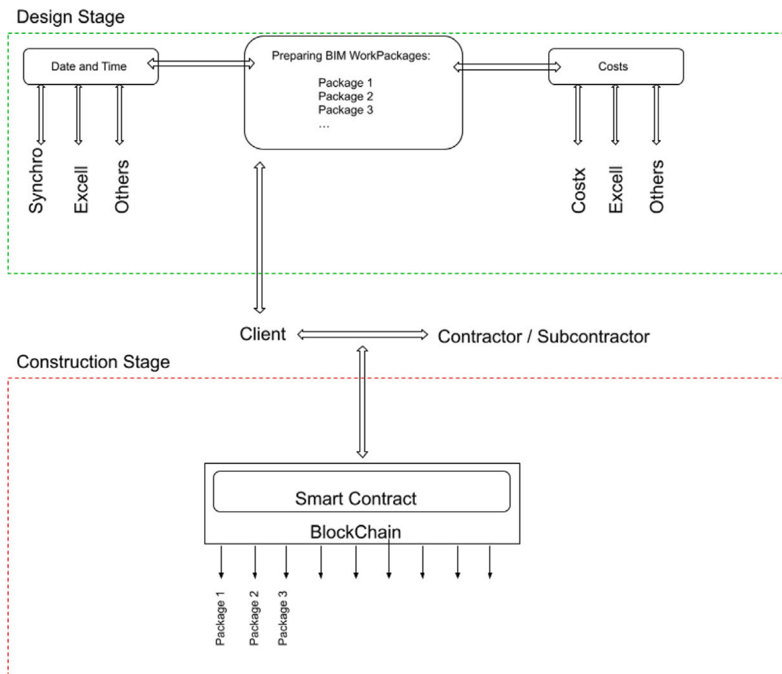

Fig. 3. Preparing BIM Work Package.

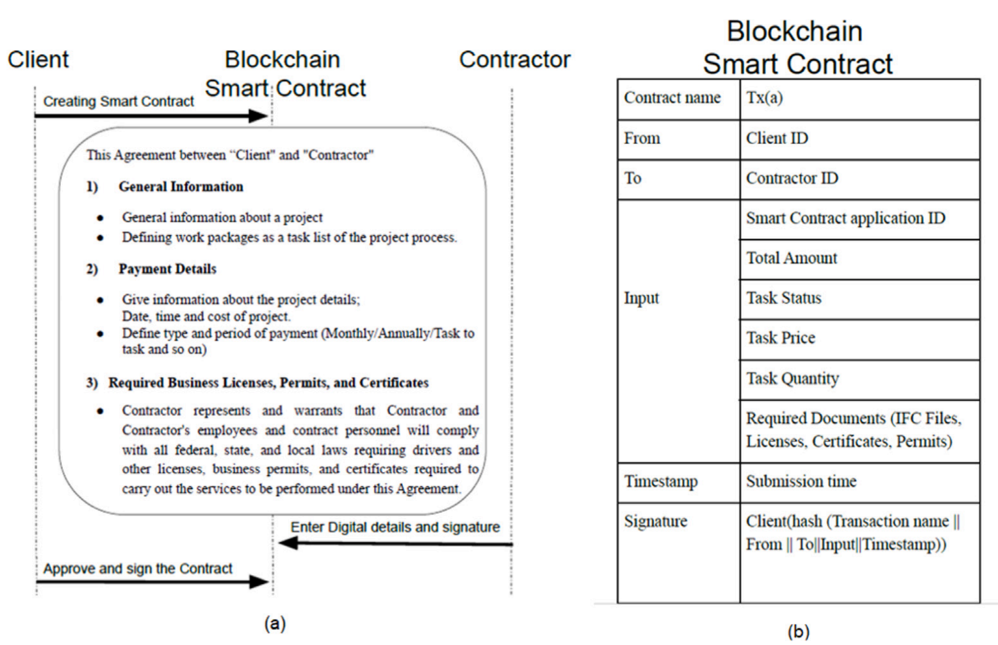

Fig. 4. Example of (a) traditional contract type and (b) smart contract type (Luo et al., 2019).

4.5. RIBA (6) handover and close out

At this stage, the project has been completed and a review process can be triggered to ensure that all the disciplines that have coexisted throughout the life of the project including a detailed analysis of the stages of the project with related history. Disciplines and participants can be assessed alongside the corresponding documents used in the project. Thus, the whole process from the beginning of the project until the handover can be under an unchangeable historical record. In addition, based on smart contracts, the process is encoded at the beginning of the project in accordance with codes of practice and the possible delays can be minimised. The contractor client and other participants will be able to use the entire process as a definitive record with the Blockchain chain, even years after the project is completed.

During the sale or delivery of the building, a smart contract is created between the Client and the Bidder to include in the Blockchain.

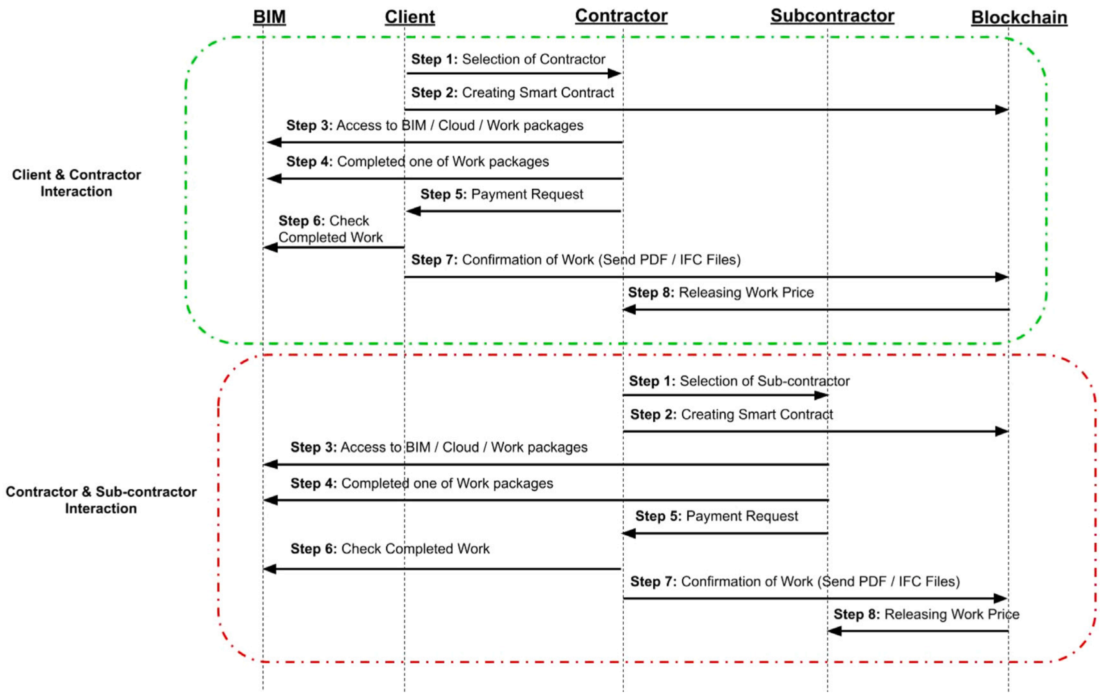

Fig. 5. Blockchain structure between Client, Contractor and Subcontractor.

All information, including required documents, and IFC files, are shared on the Blockchain and sent to the Bidder. Once the documents are shared, the Bidder approves and signs the contract so that the process is recorded in the Blockchain. The transaction is completed with the approval and signature of the recipient, that is, a party or institution registered in the Blockchain. Thus, the transfer process is recorded and completed in the Blockchain as the last record until another transaction from the operation phase arrives. In this way, all process information that receives the project or building will be able to be accessed, creating trust and transparency basis between the parties.

4.6. RIBA (7) in use

In this last stage of the RIBA Plan of Work, the project design information is released to assist in the successful operation and use of a building. Although most handover tasks are likely to be completed in Stage 6, certain activities can be necessary for the completion of the construction contract.

At this stage, it is thought that the use of technologies such as IoT will provide more contributions to the construction life cycle. The proposed structure is the same as explained in Stage 6. The only change is in relation to the contributor and the user of the Blockchain. For this stage, the use of Blockchain can be separated into different categories such as insurance, energy, maintenance, and use of vehicles and equipment.

4.6.1. Insurance scenario

Risks on construction activities and projects may be significant, and insurance can provide considerable protection for the construction disciplines. Some insurance types include employer‘s liability, flood, fire, earthquake, accident, and residual value insurance. Blockchain technology allows the use of smart contracts to automate the insurance process and minimise contract disputes as unchangeable proof of work. It can also make the process faster and optimise costs with third parties.

4.6.2. Maintenance scenario

Maintenance is the stage in which buildings and other features remain in better condition and preserved at optimum efficiency. Based on the different designs, some maintenance levels are required for product, materials, function, and location. Common types of maintenance are exterior painting, landscaping and gardening, window and door repairs, plumping and roofing tile. The Blockchain can address such maintenance aspects by decreasing intervention time and eliminating third parties. Users who need maintenance in a house or a building can use Blockchain as a trusty system to protect personal information.

4.6.3. Energy scenario

Blockchain can be adopted in all stages of the construction to address risk assessment, maintenance, and energy requirements of projects while these requirements will be categorised and listed. Regarding services (insurance, maintenance and energy) for the Client, companies will be found and invited for their bids. The Client will select the most suitable bidding at the beginning of the process. After the digital information and data sharing phase, smart contracts will be prepared between the Client and the company that won the tender. When the process is completed, the required service document and the price of the service will be sent to the Client. If the Client agrees with the proposed service and price, the contract will be approved and signed, and the financial transactions will be paid as specified in the service price. The confirmation of the agreement document and transactions will be recorded with their timestamps into the Blockchain.

4.7. Implementation of blockchain in lifecycle stages

As Blockchain technology has not yet completed its development, organisations should adopt Blockchain technology for particular applications and only where such technology can bring tangible benefits. RIBA Plan of Work is an accepted industrial process involving several stages of a construction project. Tables 1 and 2 show a general process of how to make integration with BIM and how the process develops in relation to the steps in the RIBA Work Plan. The BIM process in the table below has been prepared by considering the RIBA plan of work as identified in comparative research articles and books.

Table 1
Preparation/theory stage of blockchain.

RIBA	BIM	BLOCKCHAIN
0- Strategic Definition	• Business case and strategic brief including related core project requirements. • Establishing a Project Program for the entire life cycle of the project.	• Getting general information about Blockchain and developing appropriate use-cases (scenarios) for the project. • Advise clients on the proposes of Blockchain considering advantages and disadvantage. • Trying to find an answer to those questions: o Does the project need Blockchain? o If it is needed, which type of Blockchain can be more suitable? (Public, Private or Consortium)
1- Preparation	• Advise BIM clients by considering advantages and risks. Advise clients on the designer's requirements and integrity and scope of integrated service, including the appointment of a BIM model manager. • Define long-term responsibilities in the project construction process. • Define inputs and outputs of the BIM process and post-occupancy`s scope evaluation. • Identify scope of BIM surveys and investigate reports.	• Identify the impact of BIM and Blockchain integration on the project. • Define which Blockchain-based technology will be used in the project (Ethereum, Hyperledger, etc.) • Prepare a Blockchain-based system considering project requirements. • Define general responsibilities and duties regarding the questions: - Who will create smart contracts and control the Blockchain? - Who will coordinate BIM work packages? • Prepare the execution plan.
2- 3- 4- Design	• Consortium pre-start meeting with the stakeholders for the project. • Evaluation of strategic analysis options for initial model sharing with the design team. • Define the major design elements (such as prefabricated components), build parametric structures at the concept-level for all the main elements. • Facilitating access to BIM data for the entire design team. • Provide data sharing and integration for design coordination and detailed analysis involving data links between models. • Conduct environmental performance and region analysis using BIM data. • Facilitating project planning information from the main design to client. • Assessing project tasks with 4D and/or 5D models.	• Monitoring and managing BIM data using Blockchain records. • Recording and timestamping a BIM model for sharing with the design team including all types of project documents. • Create a smart contract with the design team and related disciplines. • Preparing and planning BIM work-packages in relation to the project specification. (See 4.3. RIBA (2,3,4) Design Stage)

We illustrate the Blockchain integration starting with preparation stages, account creation stages, duties and responsibilities showing how the process advances with various stages with the ultimate objective inform adoption in real applications. Table 1 shows the "preparation/theory stage", which covers the period from an idea to a design stage, and Table 2 demonstrates the "implementation stage", which covers the period from construction to demolishing.

5. Evaluation

The evaluation is conducted with trial data from the Clouds-for-Coordination (Petri et al., 2017) project. We use a real construction project of the Highways England involving the construction of a new bridge on A556 with data and processes provided by the project partner, Costain. The purpose of this evaluation is to demonstrate the advantages of Blockchain for a multi-disciplinary BIM project in relation to the construction of a new bridge and to demonstrate the impact of using BIM and Blockchain for supporting a more automated and efficient construction process.

5.1. Project trial

We included four project disciplines in the project trial as listed below:

- Contractor - Costain
- A cost consultant - Lee Wakemans Ltd.
- Design Team - Capita
- Client - Highways England

The construction project being discussed is a bridge system with ancillaries and includes construction disciplines that are involved in the various phases of the project.

5.2. Construction workflow with blockchain

Below we present the entire Blockchain-based coordination process between the disciplines that are part of the project.

Step 1: A decision process is necessary to decide on whether to use Blockchain for the project. The Client has decided to run the project in a BIM and Blockchain framework.

Step 2: The Client sets up the Blockchain with the following details; name, address, profile, transaction details.

Step 3: The design team creates and prepares a BIM model and work packages with the required information taken from a BIM model.

Step 4: The work packages have been transformed into codes for the Blockchain smart contract and synchronised with the BIM model and software.

Table 2
Implementation Stage of Blockchain.

5- Construction	• Exporting BIM data including offsite manufacturing and on-site Construction according to Construction Programme. • Enable data sharing for disciplines participating in the project. • Integrating and analysing a detailed BIM model. • Enable BIM model`s accessibility to Contractor(s) and Subcontractor(s). • Review with the Contractor based on the construction sequence (4D). • Agree timing and scope of ``Soft Landings''. • Coordinate and release of ``End of construction'' BIM record model data. • Use of 4D/5D BIM data for the purposes of project administration.	• Create a smart contract with Contractor and Subcontractors and additional disciplines that are involved in the project. • Recording and tracking completed BIM work packages and associated transactions. • Controlling and checking BIM updates and transactions associated with BIM work-packages
6- Handover & Closeout	• Performing the necessary procedures for the handover of the building. • Conclusion of the construction contract and handover process. • Study of information on parametric objects contained within the data of the BIM model.	• Creating smart contracts for handover stage and for managing transactions. • Sending building documents to the Blockchain as to record events and to make a immutable data record.
7- In Use	• Undertake ``in-use'' services according to the ``Schedule of Services''. • Provide feedback and maintain a continuous relationship with the Client until the end of the building lifecycle.	• Setting auto-payment system for regular payment. • Creating Smart Contracts for payment services. • *Insurance:* Auto-payment can be set for regular payment. • *Maintenance:* Blockchain can be used for recording the maintenance of a building including immutable history and associated payments without third parties. • *Energy:* Blockchain along with artificial intelligence (AI) techniques can identify consumer energy behaviours and forecast energy demand

Step 5: The Client will find the most suitable Contractor. Both the Client and the Contractor will share their digital information such as profile and hash.

Step 6: The smart contract will be prepared between the Client and the Contractor. The Contract will include general information about work, due date, cost and so on.

Step 7: The Contractor will get permission to access the BIM model and work packages, which have been prepared in the project design stage by the design team.

Step 8: The Contractor will start to complete the work packages. When all workpackages are completed, the notifications will be sent to both the Client and the Contractor.

Step 9: When the tasks and work packages are completed, the smart contract executes itself and the BIM model with the IFC files are recorded to the Blockchain.

Step 10: At the end of the process, the amount of money which has been specified in the smart contract will be released. Thus, transactions and documents will be all recorded into the Blockchain.

When the Contractor needs a Subcontractor for the work packages, the Contractor can find a Subcontractor, and the same process will be repeated between the Contractor and the Subcontractor from creating the smart contract to the end of the package. This process is delivered using a design tool such as Revit and can be managed as a part of a multidisciplinary federated cloud. All participants of the project join the cloud as a different cloud node where users of the cloud node will see the BIM model based on different levels of visibility. The construction project workflow is presented in Fig. 6.

5.3. Trial and validation

Within this subsection, we present the entire Blockchain scenario, including disciplines and implementations which were delivered within the project trial as shown in Fig. 7.

As stated, four disciplines are used with the below annotations: discipline C — Contractor, discipline Q — Cost Consultant, discipline E — Design Team, and discipline O — Client.

5.3.1. Prerequisites

We use Ethereum as a Blockchain solution to allow project participants from different disciplines to establish smart contracts and keep changes tracked on the same ledger. We use the Remix compiler to deliver the implementation of smart contracts. In our study, we use data blocks to facilitate transfers by encrypting with hash data and encrypting with a disciplinary digital signature. We have used a hash function to encode the metadata in the current block, including the signature and information about the process of connecting blocks in the Blockchain. Whenever a new block is generated in the database, the previous block's hash value is combined with the latest block's details, and a new hash is created and signed with the user's digital signature. The following workflow demonstrates how a smart contract may be used to synchronise the design documents of the various disciplines participating in a building project.

• The Architect generates a URL for an IFC file that is being sent to the design record database in the form of a document library (hyperlink)

• Using a Blockchain API, the Architect digitally signs the contract and generates a special cryptographic hash.

• The architect generates a new contract in the distributed ledger for the system, and the client is assigned as a reviewer.

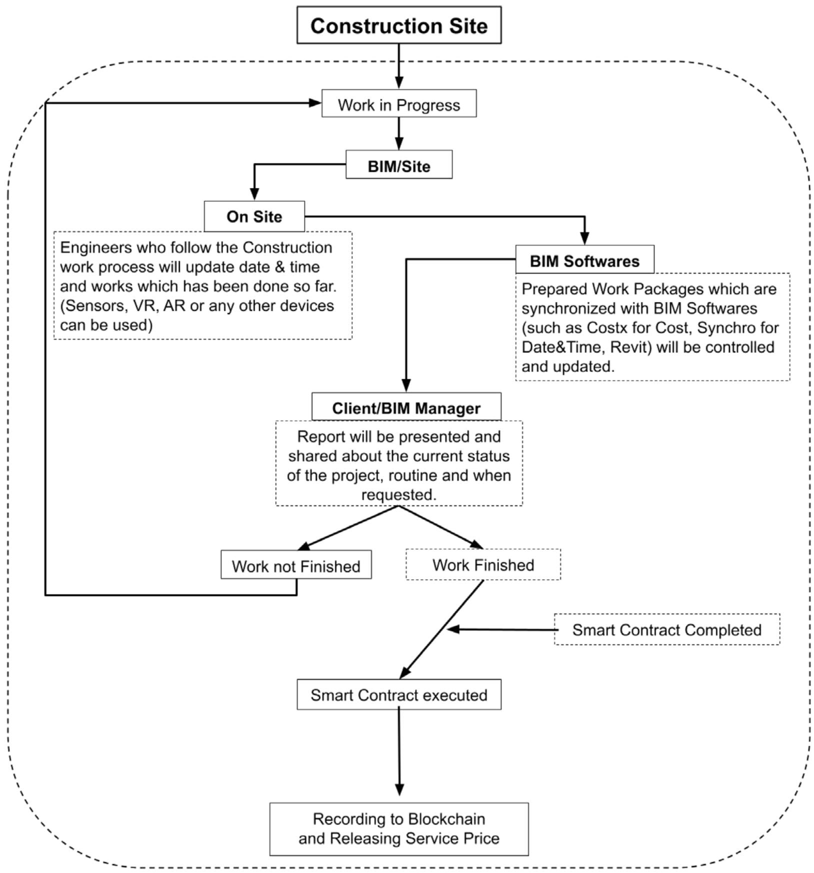

Fig. 6. Blockchain supported project workflow.

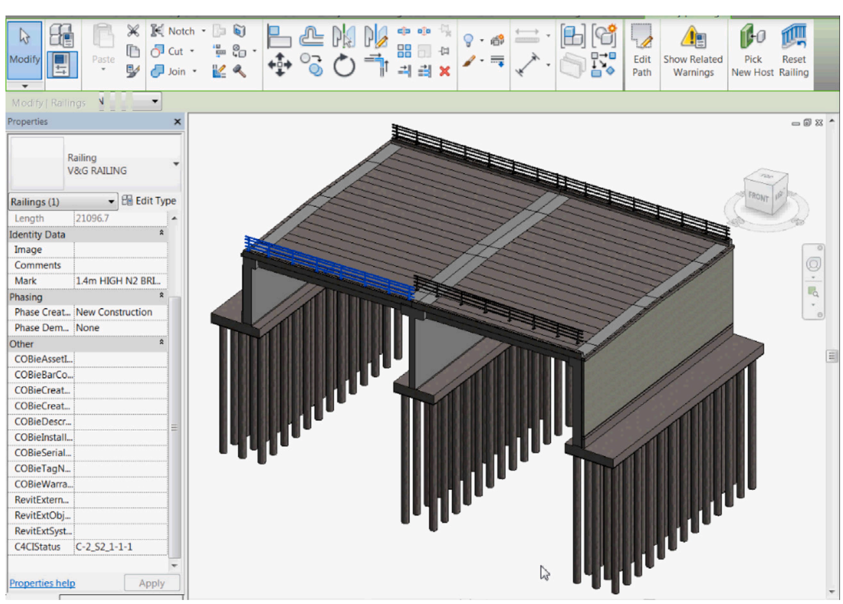

Fig. 7. The bridge design model.

• If the client has signed the contract, the client may get an email with a guide to see the contract as to decline or approve the proposal.

• If the client decides to proceed, it is requested to complete the registration.

Bridge Model - Package 8	Quantity	Cost
EXTERNAL WORKS		**639,735.84**
8.1 – Site Preparation		**2,523.30**
8.1.1 – Cleaning vegetation	504.66 m^2	2,523.30
8.2 – Fencing, Railing and Walls		**637,212.54**
8.2.1 – Walls and Screens	29.86 m	14,930.00
8.2.2 – Retaining Walls	29.86 m	22,395.00
8.3 – Piling		**574,558.54**
8.3.1 – Piling mats/ platforms	179.18 m^2	89,590.00
8.3.2 – Piling plant	1.00 IT	16,000.00
8.3.3 – Piles	104.00 Nr	188,240.00
8.3.4 – Disposal of exc. mat	1,190.02 m^3	35,700.60
8.3.5 – Cutting off tops on concrete piles	1.00 IT	3,120.00
8.3.6 – Pile tests	5.20 Nr	44,200.00
8.3.7 – Vibro-compacted columns	104.00 Nr	1,560.00
8.3.8 – Pile Caps	3 Nr	196,147.94
8.4 – Barriers and guardrails		**25,329.00**
8.4.1 – Vehicle restraint systems	84.43 m	25,329.00

Fig. 8. Bridge Model External Works Work Package – 8.

• After signing the contract registration, the original smart contract is recorded, and a new fully fulfilled contract is created in the distributed ledger where the two parties enter the contract.

• The smart contract is updated to match a database URL, and the final link to the document is generated with a unique reference

Instalments: To run the Ethereum network, users need to first register with the network and initiate the first chain. The Blockchain network has a set of rules for the first block, also known as the genesis block. The Genesis.json file provides an explanation for the Ethereum network. To fully start the Network, a client ID is created in the P2P network, followed by the wallet that will be used to process the transactions. The network is started and the next step is to create a smart contract to be written and compiled.

Step 0 - Discipline O: The "Discipline O" defines who is allowed to view and shared the data, and then defines what is shared.

Step 1 - Discipline E: The process begins with "Discipline E" which generates a first bridge BIM model object that syncs with the system. Then the discipline uploads the generated ifc file "A556-CAP-7000-S06-3D-S-1001.ifc" and shares with project collaborators.

Step 2 - Discipline O: "Discipline O" converts the prepared work package tasks, which have been prepared by "Discipline E" and "Discipline Q", to the computer code for smart contracts. For our trial, "Bridge Model - Package 8 (External Works)" has been selected to code for the smart contract as demonstrated in Fig. 8.

Step 3 - Discipline C: "Discipline C" works on-site and attempts to complete the task by updating the BIM model and verifying the process. When the contract task "Barriers and Guardrails" and the rest of the tasks are complete, the smart contract automatically executes itself ("Discipline O" can check the updates and sign the contract before payment) and notifications will be circulated to related disciplines, and the final IFC file "A556-CAP-7000-S06-3D-S-1001.ifc" will be recorded to the Blockchain. Then, the amount specified by the payment transaction is released. The coding associated with the work package is presented in Fig. 9.

Contract name	**Bridge Model - Package 8 (External Works)**
From	(Client ID)
To	(Contractor ID)
Input	**BIMPackage8**
	639,735.84 (Package total amount)
	(Package tasks) **8.1. Site Preparation** [X] **8.2. Fencing, Railing and Walls** [X] **8.3. Pilling** [X] **8.4. Barriers and Guardrails** [ ]
	A556-CAP-7000-S06-3D-S-100.ifc (Project file)
Signature	**Client(hash (BIMPackage8 || Client|| Contractor||Timestamp))**

Fig. 9. Work package into codes for the smart contract.

The validation is accomplished using four discipline users also called "discipline nodes" that exchange project data as in the project trial reported in Sections 5.1–5.3. Each user has been allocated a hash of the activity and private key and a signature algorithm to sign the hash. Both the activity and the digital signature are accessible to the receivers and to the record system, which can then validate the transaction's orientation towards the signature using both the sender's public key and the activity's hash. True is returned by the validation procedure only if the sender's signature and operation hash are the same, indicating that they were the ones who submitted the activity. It is possible that the records have been tampered with or that the signature has been forged if this algorithm returns false. A system of charges and incentives is used to increase the likelihood that the Blockchain network includes only valid blocks of transactions. When a discipline node introduces new records to the Blockchain network, the information is disseminated to all other nodes in the network. Following the validation of the transactions, each node starts the process of collecting the data into a new block of transactions. As a result, the Blockchain system keeps track of all interactions and activities among users. The Ethereum test network is used to verify the validity of the information as a repository for data from disciplines and activities and smart contracts for data validation based on consensus and contract transfers through programming code, and the SHA-256 algorithm to retrieve data from records and activities.

5.4. Blockchain deployment

The smart contract enables the creation, storage, and retrieval of package structs and provides a transparent and immutable method for tracking and managing work packages on the Ethereum Blockchain.

Solidity, a language used to generate smart contracts on the Ethereum network, is used to create a smart contract for the "BIMPackage8" workpackage (see Appendix A.1). The contract includes a user-defined data structure named "Package" that contains the information associated with a work package. The "Package" structure has many elements, including "sender" and "receiver", which are strings used to hold the Ethereum addresses of the work package's sender and receiver respectively. In addition, the structure comprises a "name" text field that stores the name of the work package and an "amount" that stores the financial value of the work package. In addition, the "projectFile" element is a string providing the location of the project file affiliated with the work package. The last field, "completed", is a Boolean value that indicates whether or not the work package has been completed.

The code has been run inside the Remix environment and is seen to work as predicted, based on the code's specification of intended behaviour. The successful execution of the code in the Remix environment may be seen as evidence that the code is functional and prepared for deployment on the Ethereum blockchain, this can be seen in Listing 1.

Listing 1: Example of the successful execution of the smart contract

```
{
"string _sender": "0x5B38Da6a701c568545dCfcB03FcB875f56beddC4",
"string _receiver": "0xf8e81D47203A594245E36C48e151709F0C19fBe8",
"string _name": "BIMPackage8",
"uint256 _amount": "639735",
"string _projectFile": "A556—CAP—7000—S06—3D—S—1001.ifc"
}
```

In Listing 2, the "topic" entry is a string representing the event's unique identification, which is used to specify the event type. The "event" parameter is a string that records the event's name, "PackageCompleted" in this case. After the tasks are completed, it can be seen that the smart contract is automatically executed and the package is completed successfully.

The listing provided in the code may be used to indicate an event that has been produced by a smart contract, including information about the event's origin, its type, and any relevant parameters. This enables other parties to respond to and analyse the data provided by the Blockchain network, offering a method to track and monitor the contract's status.

In Listing 3, the smart contract emits the event "PackageDueDateExecuted", which contains information about the package whose due date has arrived. The event receives the package address and package name as inputs, which may be used to identify the package that has passed its due date. This event may be used to initiate various actions, such as altering the package's status or alerting the appropriate parties that the package's due date has passed.

A test environment was created to analyse interactions and transactions between clients, architects, structural engineers, and MEP (Mechanical, Electrical, and Plumbing) engineers (MEP is considered as one discipline). The test environment was created to simulate real-world scenarios, and the data gathered throughout the testing process was utilised to assess the performance and cost-effectiveness of completing transactions in this environment.

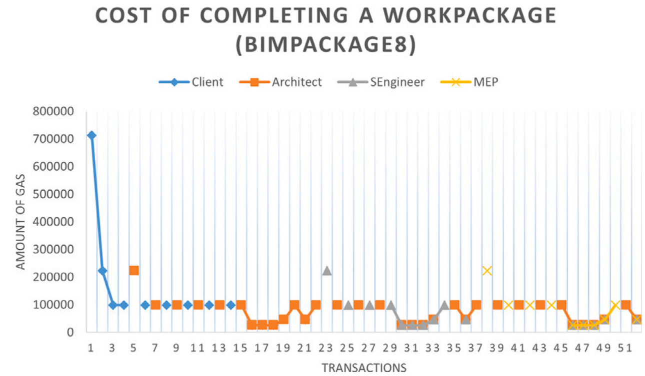

Fig. 10. Workpackage (BIMPackage8) completion cost.

During the test, a total of 81 transactions were executed amongst the various disciplines (Fig. 10 indicates that there are 51 transactions since some transactions happen simultaneously with others). These exchanges were recorded, and the resulting data were evaluated to determine the overall gas price associated with interactions. The gas price is a measure of the cost of completing an Ethereum Blockchain transaction, and it is commonly calculated in Wei, the smallest unit of Ethereum.

The smart contract has a certain allowance of gas spent depending on the number of actions performed and the gas price of the requested codes. There is no standard fixed conversion price in the smart contract and the process of determining any gas price depends on the sender and the quality of the code being written. According to the test findings, the total price of gas associated with the 81 activities was 6270082 Wei. This sum of Wei may be translated to other Ethereum units, such as Ether, for easy comparison. In this case, it is indicated that 6270082 Wei is equal to 0.006270082 Ethereum, and the value to US dollars using the current exchange rate is 8.89 US dollars (1 Ethereum = 1417.13 US Dollar, 13.01.2023). For the completing cost for the workpackage (BIMPackage8) is given with the interactions in Fig. 10

The model we propose in this section demonstrates the use of Blockchain in construction projects and its contribution to BIM-based multi-disciplinary collaboration. We provide a comprehensive framework applicable to the construction industry that addresses the problem of payment delays and contract disputes. We use smart contracts for the life cycle of the construction process where tasks are created and coded based on smart contracts in order to make the process more 'functional' and automated. With the smart contract and time stamp registration in the ledger, disputes arising from the contract can be minimised as BIM and Blockchain will strengthen the collaboration with a highly secure interaction between Client, Contractor and Subcontractor, and provide reliable information and sharing ecosystem of BIM data. This can further strengthen cooperation between all stakeholders by eliminating third parties and minimising costs.

6. Conclusion and future work

This research contributes to the ongoing effort to understand Blockchain with its current state-of-the-art technology and its subsequent use for the digitalisation of the construction industry. Two research questions were posited to address the aim of the paper. In response to RQ1 (What is the application and level of integration of Blockchain and BIM in the construction industry?), an in-depth literature review was conducted that concluded that the use of Blockchain in Construction is sparse, limited, and still in its infancy. Current initiatives are still in the research and development stage, with a number of limitations and blockers identified. As to RQ2 (Can the integration of BIM and Blockchain offer a lifecycle and supply chain approach to address construction industry limitations and blockers?), we propose a Blockchain and BIM integration model that has the po-

Listing 2: Example of the execution of smart contract when the workpackage completed


```
{
"from": "0xf8e81D47203A594245E36C48e151709F0C19fBe8",
"topic": "0x61056d12ef421e98b7b702b8ff2015dbad4b45ef362e58eb0b59e2fdcbfe2b39",
"event": "PackageCompleted",
"args": {
 "0": "0xAb8483F64d9C6d1EcF9b849Ae677dD3315835cb2",
 "1": "",
 "packageAddress": "0xAb8483F64d9C6d1EcF9b849Ae677dD3315835cb2",
 "packageName": ""
    }
}
```


Listing 3: Example of the smart contract execution on work package deadline


```
{
"from": "0xf8e81D47203A594245E36C48e151709F0C19fBe8",
"topic": "0xb04ed2344cc68716471b1d42367e0fd3d3c911a465219fdda504ede34d5c383e",
"event": "PackageDueDateExecuted",
"args": {
 "0": "0x5B38Da6a701c568545dCfcB03FcB875f56beddC4",
 "1": "BIMPackage8",
 "packageAddress": "0x5B38Da6a701c568545dCfcB03FcB875f56beddC4",
 "packageName": "BIMPackage8"
 }
}
```


tential to improve the construction collaboration process and eliminate third parties to avoiding delays while ensuring that transactions are highly secure, transparent, and traceable. We have demonstrated that a Blockchain-based system ensures that BIM data exchanges can be securely performed with approved confidentiality and trust mechanisms can ensure fast and robust operations. The work is validated on a real construction project with multiple participants enabling a collaborative and secure environment by integrating Blockchain with BIM in an exemplar case study. The proposed framework is meant to increase trust among stakeholders at all stages of the construction process and to provide a safer environment to minimise possible delays by regularly monitoring payments with a smart contract while minimising disputes that may occur with unchangeable records. This comes as a step forward to support construction stakeholders to develop a robust data infrastructure necessary to digitalise the construction process.

This study also aims to further advance the existing state-of-the-art research on Blockchain by proposing a roadmap mechanism for implementing Blockchain in the construction industry. We show how creating work packages during the design process and making this creation process connected with BIM can automatically improve the process. In such a digital ecosystem, construction stakeholders can manage their resources better and minimise recording documents and timestamps by the use of smart contracts and Blockchain.

Overall, this study provides the following two main contributions:

- It conducts an in-depth literature survey assessing perceived barriers and possible applications for adopting Blockchain for construction management;
- It provides a best-practice case study informed from a real construction project as a mean to demonstrate the integration of Blokchain and BIM for multidisciplinary project collaboration;

Blockchain provides several benefits such as simplicity, flexibility, and user-defined policies that can enable code control compatibility in BIM workflows and a more secure and automated construction process. Thus, for the construction industry, Blockchain contributes to accelerating the digitalisation of processes and applications greatly improving the traceability of tasks and resources involved in a construction project. In this way, the misalignment of contracts can be minimised, and corrective actions can be implemented timely. Moreover, the accuracy of costs and timing estimates can significantly increase the reliability of a Blockchain supported construction project. Together with these advantages, Blockchain can also increase overall productivity paving the way toward a more digitalised and automated construction ecosystem. Further research involves extending the Computational Urban Sustainability Platform (CUSP) developed by the authors (Rezgui et al., 2021) to include Blockchain related services to support stakeholders' transactions across the project and building lifecycle, taking into account the concept of Material Passport and recyclability. These developments will be reported in follow-on publications.

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.

Data availability

No data was used for the research described in the article.

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Appendix

A.1. Code of the smart contract used for the workpackage

```
pragma solidity ^0.8.0;

contract WorkPackage {
    // Structure to hold information about a work package
    struct Package {
        string sender;
        string receiver;
        string name;
        uint amount;
        string projectFile;
        bool completed;
    }

    // Mapping to store all work packages
    mapping (address => Package) packages;

    // Events for package completion and due date execution
    event PackageCompleted(address indexed packageAddress,
        string packageName);
    event PackageDueDateExecuted(address indexed packageAddress,
        string packageName);

    // Function to add a new work package
    function addPackage(string memory _sender, string memory _receiver,
        string memory _name, uint _amount, string memory _projectFile)
        public {
        packages[msg.sender] = Package(_sender, _receiver, _name,
        _amount, _projectFile, false);
    }

    // Function to mark a work package as completed
    function completePackage(address _packageAddress) public {
        require(packages[_packageAddress].completed == false,
        "Package already completed");
        packages[_packageAddress].completed = true;
        emit PackageCompleted(_packageAddress, packages[_packageAddress].name);
    }

    // Function to execute a package when its due date is reached
    function executeDueDate(address _packageAddress) public {
        require(packages[_packageAddress].completed == false,
     "Package already completed");
        emit PackageDueDateExecuted(_packageAddress,
            packages[_packageAddress].name);
    }
}
```

References

Andrian, H.R., Kurniawan, N.B., et al., 2018. Blockchain technology and implementation: A systematic literature review. In: 2018 International Conference on Information Technology Systems and Innovation. ICITSI, IEEE, pp. 370–374. http://dx.doi.org/10.1109/ICITSI.2018.8695939.

Anon, 2019. Blockchain in the built environment and construction industry: A systematic review, conceptual models and practical use cases. Autom. Constr. 102, 288–307. http://dx.doi.org/10.1016/j.autcon.2019.02.005.

Anon, 2023a. Digitalised circular construction supply chain: An integrated BIM-blockchain solution. Autom. Constr. 148, 104746. http://dx.doi.org/10.1016/j.autcon.2023.104746.

Anon, 2023b. Suitability analysis of consensus protocols for blockchain-based applications in the construction industry. Autom. Constr. 145, 104638. http://dx.doi.org/10.1016/j.autcon.2022.104638.

Belle, I., 2017. The architecture, engineering and construction industry and blockchain technology. In: Digital Culture, Conference on Digital Technologies in Architectural Education and DADA 2017 International Conference on Digital Architecture. China Architecture Industry, Nanjing, China, pp. 279–284, URL.

Berryhill, J., Bourgery, T., Hanson, A., 2018. Blockchains Unchained: Blockchain Technology and Its Use in the Public Sector. OECD, http://dx.doi.org/10.1787/19934351.

Chauhan, B.K., Patel, D.B., 2022. A systematic review of blockchain technology to find current scalability issues and solutions. In: Proceedings of Second Doctoral Symposium on Computational Intelligence. Springer, pp. 15–29. http://dx.doi.org/10.1007/978-981-16-3346-1_2.

Cheng, M., Liu, G., Xu, Y., Chi, M., 2021. When blockchain meets the AEC industry: Present status, benefits, challenges, and future research opportunities. Buildings 11, 340. http://dx.doi.org/10.3390/buildings11080340.

Chynoweth, P., Christensen, S., McNamara, J., O'Shea, K., 2007. Legal and contracting issues in electronic project administration in the construction industry. Struct. Surv. 25, 191–203. http://dx.doi.org/10.1108/02630800710772791.

Cole, R., Stevenson, M., Aitken, J., 2019. Blockchain technology: Implications for operations and supply chain management. Supply Chain Manag.: Int. J. 24 (4), 469–483. http://dx.doi.org/10.1108/scm-09-2018-0309.

Dakhli, Z., Lafhaj, Z., Mossman, A., 2019. The potential of blockchain in building construction. Buildings 9, 77. http://dx.doi.org/10.3390/buildings9040077.

Das, M., Tao, X., Cheng, J.C., 2021. BIM security: A critical review and recommendations using encryption strategy and blockchain. Autom. Constr. 126, 103682. http://dx.doi.org/10.1016/j.autcon.2021.103682.

Dounas, T., Lombardi, D., Jabi, W., 2020. Framework for decentralised architectural design, BIM and blockchain integration. Int. J. Archit. Comput. 19, http://dx.doi.org/10.1177/1478077120963376.

Drljevic, N., Aranda, D.A., Stantchev, V., 2020. Perspectives on risks and standards that affect the requirements engineering of blockchain technology. Comput. Stand. Interfaces 69, 103409. http://dx.doi.org/10.1016/j.csi.2019.103409.

El Khatib, M., Al Mulla, A., Al Ketbi, W., 2022. The role of blockchain in E-governance and decision-making in project and program management. Adv. Internet Things 12 (3), 88–109. http://dx.doi.org/10.4236/ait.2022.123006.

Elbashbishy, T.S., Ali, G.G., El-adaway, I.H., 2022. Blockchain technology in the construction industry: sapping current research trends using social network analysis and clustering. Constr. Manag. Econ. 40, 406–427. http://dx.doi.org/10.1080/01446193.2022.2056216.

Elghaish, F., Abrishami, S., Hosseini, M.R., 2020. Integrated project delivery with blockchain: An automated financial system. Autom. Constr. 114, 103182. http://dx.doi.org/10.1016/j.autcon.2020.103182.

Erri Pradeep, A., Yiu, T., Amor, R., 2019. Leveraging blockchain technology in a BIM workflow: A literature review. In: International Conference on Smart Infrastructure and Construction 2019 (ICSIC) Driving Data-Informed Decision-Making. pp. 371–380. http://dx.doi.org/10.1680/icsic.64669.371.

Erri Pradeep, A.S., Yiu, T.W., Zou, Y., Amor, R., 2021. Blockchain-aided information exchange records for design liability control and improved security. Autom. Constr. 126, 103667. http://dx.doi.org/10.1016/j.autcon.2021.103667.

Figueiredo, K., Hammad, A.W., Haddad, A., Tam, V.W., 2022a. Assessing the usability of blockchain for sustainability: Extending key themes to the construction industry. J. Clean. Prod. 131047.

Figueiredo, K., Hammad, A.W., Haddad, A., Tam, V.W., 2022b. Assessing the usability of blockchain for sustainability: Extending key themes to the construction industry. J. Clean. Prod. 343, 131047. http://dx.doi.org/10.1016/j.jclepro.2022.131047.

Ganter, M., Lützkendorf, T., 2019. Information management throughout the life cycle of buildings – Basics and new approaches such as blockchain. 323, 012110. http://dx.doi.org/10.1088/1755-1315/323/1/012110,

Graham, S., Hailer, J.D., 2019. Implementation of Blockchain Technology Inthe Construction Industry. URL https://digitalcommons.calpoly.edu/cmsp/190.

Gurtu, A., Johny, J., 2019. Potential of blockchain technology in supply chain management: A literature review. Int. J. Phys. Distrib. Logist. Manage. http://dx.doi.org/10.1108/IJPDLM-11-2018-0371.

Hamledari, H., Fischer, M., 2020. Role of blockchain-enabled smart contracts in automating construction progress payments. J. Legal Aff. Dispute Resolut. Eng. Construct. 13, 04520038. http://dx.doi.org/10.1061/(ASCE)LA.1943-4170.0000442.

Hamledari, H., Fischer, M., 2021. Construction payment automation using blockchain-enabled smart contracts and robotic reality capture technologies. Autom. Constr. 132, 103926. http://dx.doi.org/10.1016/j.autcon.2021.103926.

Hammi, A., Bouras, A., 2018. Towards safe-BIM curricula based on the integration of cybersecurity and blockchains features. pp. 2380–2388. http://dx.doi.org/10.21125/inted.2018.0453.

Heiskanen, A., 2017. The technology of trust: How the Internet of Things and blockchain could usher in a new era of construction productivity. Construct. Res. Innov. 8, 66–70. http://dx.doi.org/10.1080/20450249.2017.1337349.

Hijazi, A.A., Perera, S., Alashwal, A., Calheiros, R.N., 2019. Blockchain adoption in construction supply chain: A review of studies across multiple sectors. In: Constructing Smart Cities: Proceedings of the 22nd CIB World Building Congress. CIB2019, 17-21 June 2019, The Hong Kong Polytechnic University, Hong Kong, China, URL https://researchdirect.westernsydney.edu.au/islandora/object/uws%3A55406.

Hijazi, A., Perera, S., Calheiros, R., Alashwal, A., 2021. Rationale for the integration of BIM and blockchain for the construction supply chain data delivery: A systematic literature review and validation through Focus Group. J. Construct. Eng. Manag. 147, http://dx.doi.org/10.1061/(ASCE)CO.1943-7862.0002142.

Ho, s., Liu, L., 2004. Analytical model for analyzing construction claims and opportunistic bidding. J. Constr. Eng. Manag. 130, 94–104. http://dx.doi.org/10.1061/(ASCE)0733-9364(2004)130:1(94).

Iansit, M., Lakhani, K.R., 2019. The truth about blockchain. Harv. Bus. Rev. URL https://hbr.org/2017/01/the-truth-about-blockchain.

Kang, K., Liu, X., Jiang, Y., Lee, K., Wan, S., Huang, G.Q., Zhong, R., 2022. Blockchain opportunities for construction industry in Hong Kong: A case study of RISC and site diary. Construct. Innov. http://dx.doi.org/10.1108/CI-08-2021-0153.

Keskin, B., Salman, B., Ozorhon, B., 2021. Airport project delivery within BIM-centric construction technology ecosystems. Eng. Constr. Archit. Manag. 28, 530–548. http://dx.doi.org/10.1108/ECAM-11-2019-0625.

Koseoglu, O., Keskin, B., Ozorhon, B., 2019. Challenges and enablers in BIM-enabled digital transformation in mega projects: The Istanbul new airport project case study. Buildings 9, http://dx.doi.org/10.3390/buildings9050115.

Krämer, M., Besenyői, Z., 2018. Towards digitalization of building operations with BIM. IOP Conf. Ser.: Mater. Sci. Eng. 365, 022067. http://dx.doi.org/10.1088/1757-899X/365/2/022067.

Kuperberg, M., Geipel, M., 2021. Blockchain and BIM (Building Information Modeling): Progress in Academia and Industry. http://dx.doi.org/10.48550/arXiv.2104.00547.

Li, J., Greenwood, D., Kassem, M., 2019a. Blockchain in the built environment and construction industry: A systematic review, conceptual models and practical use cases. Autom. Constr. 102, 288–307. http://dx.doi.org/10.1016/j.autcon.2019.02.005.

Li, J., Kassem, M., Ciribini, A., Bolpagni, M., 2019b. A proposed approach integrating DLT, BIM, IoT and smart contracts: Demonstration using a simulated installation task. http://dx.doi.org/10.1680/icsic.64669.275.

Li, C., Zhang, Y., Xu, Y., 2022. Factors influencing the adoption of blockchain in the construction industry: A hybrid approach using PLS-SEM and fsQCA. Buildings 12 (9), http://dx.doi.org/10.3390/buildings12091349.

Liu, H., Han, S., Zhu, Z., 2023. Blockchain technology toward smart construction: Review and future directions. J. Construct. Eng. Manag. 149 (3), 03123002. http://dx.doi.org/10.1061/JCEMD4.COENG-11929.

Lohmer, J., Lasch, R., 2020. Blockchain in operations management and manufacturing: Potential and barriers. Comput. Ind. Eng. 149, 106789. http://dx.doi.org/10.1016/j.cie.2020.106789.

Lohry, M., Bodell, B., 2015. Blockchain enabled co-housing. URL https://medium.com/@MatthewLohry/blockchain-enabled-co-housing-de48e4f2b441.

Luo, H., Das, M., Wang, J., Cheng, J., 2019. Construction payment automation through smart contract-based blockchain framework. In: ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction, Vol. 36. IAARC Publications, pp. 1254–1260. http://dx.doi.org/10.22260/ISARC2019/0168.

Mahmudnia, D., Arashpour, M., Yang, R., 2022. Blockchain in construction management: Applications, advantages and limitations. Autom. Constr. 140, 104379. http://dx.doi.org/10.1016/j.autcon.2022.104379.

Mason, J., 2019. BIM fork: Are smart contracts in construction more likely to prosper with or without BIM? J. Legal Aff. Dispute Resolut. Eng. Construct. 11, 02519002. http://dx.doi.org/10.1061/(ASCE)LA.1943-4170.0000316.

Nanayakkara, S., Perera, S., Bandara, D., Weerasuriya, T., Ayoub, J., 2019. Blockchain technology and its potential for the construction industry. http://dx.doi.org/10.6084/m9.figshare.10315331.v3.

Nawari, N.O., Ravindran, S., 2019a. Blockchain and the built environment: Potentials and limitations. J. Build. Eng. 25, 100832. http://dx.doi.org/10.1016/j.jobe.2019.100832.

Nawari, N.O., Ravindran, S., 2019b. Blockchain technologies in BIM workflow environment. In: Computing in Civil Engineering 2019: Visualization, Information Modeling, and Simulation. American Society of Civil Engineers Reston, pp. 343–352. http://dx.doi.org/10.1061/9780784482421.044.

Ni, Y., Sun, B., Wang, Y., 2021. Blockchain-based BIM digital project management mechanism research. IEEE Access 9, 161342–161351. http://dx.doi.org/10.1109/ACCESS.2021.3130270.

Nikologianni, A., Mayouf, M., Gullino, S., 2022. Building Information Modelling (BIM) and the impact on landscape: A systematic review of evolvements, shortfalls and future opportunities. Clean. Prod. Lett. 3, 100016. http://dx.doi.org/10.1016/j.clpl.2022.100016.

Niya, S.R., Schüpfer, F., Bocek, T., Stiller, B., 2018. A peer-to-peer purchase and rental smart contract-based application (PuRSCA). It - Inf. Technol. 60, 307–320. http://dx.doi.org/10.1515/itit-2017-0036.

Panetta, K., 2019. The CIO's Guide to Blockchain. Smarter with Gartner, URL https://www.gartner.com/smarterwithgartner/the-cios-guide-to-blockchain/.

Penzes, B., 2018. Blockchain technology in the construction industry. http://dx.doi.org/10.13140/RG.2.2.14164.45443.

Perera, S., Nanayakkara, S., Rodrigo, M., Senaratne, S., Weinand, R., 2020. Blockchain technology: Is it hype or real in the construction industry? J. Ind. Inf. Integr. 17, 100125. http://dx.doi.org/10.1016/j.jii.2020.100125.

Petri, I., Beach, T., Rezgui, Y., Wilson, I.E., Li, H., 2014. Engaging construction stakeholders with sustainability through a knowledge harvesting platform. Comput. Ind. 65, 449–469. http://dx.doi.org/10.1016/j.compind.2014.01.008, ICT for Sustainability in Industry.

Petri, I., Rana, O.F., Beach, T., Rezgui, Y., 2017. Performance analysis of multi-institutional data sharing in the Clouds4Coordination system. Comput. Electr. Eng. 58, 227–240. http://dx.doi.org/10.1016/j.compeleceng.2017.02.015.

Prewett, K.W., Prescott, G.L., Phillips, K., 2020. Blockchain adoption is inevitable—Barriers and risks remain. J. Corporate Account. Finance 31 (2), 21–28. http://dx.doi.org/10.1002/jcaf.22415.

Ramachandran, G.S., Krishnamachari, B., 2018. Blockchain for the IoT: Opportunities and challenges. arXiv preprint arXiv:1805.02818.

Rejeb, A., Rejeb, K., Keogh, J.G., Zailani, S., 2022. Barriers to blockchain adoption in the circular economy: A fuzzy Delphi and best-worst approach. Sustainability 14 (6), http://dx.doi.org/10.3390/su14063611.

Rezgui, Y., Beach, T.H.O., Petri, I., Hippolyte, J.-l., Ahmad, M.W., Wanqing, Z., Howell, S., 2021. Autonomous and semantic optimization approach for real-time performance management in a built environment. Google Patents, US Patent App. 16/513, 471.

Rodrigo, M., Perera, S., Senaratne, S., Jin, X., 2018. Blockchain for construction supply chains: A literature synthesis. In: Proceedings of ICEC-PAQS Conference 2018. URL https://researchdirect.westernsydney.edu.au/islandora/object/uws:49027.

San, K.M., Choy, C.F., Fung, W.P., 2019. The potentials and impacts of blockchain technology in construction industry: A literature review. IOP Conf. Ser.: Mater. Sci. Eng. 495, 012005. http://dx.doi.org/10.1088/1757-899X/495/1/012005.

Shojaei, A., 2019. Exploring applications of blockchain technology in the construction industry. Proc. Int. Struct. Eng. Construct. 6, http://dx.doi.org/10.14455/ISEC.res.2019.78.

Shojaei, A., Flood, I., Izadi Moud, H., Hatami, M., Zhang, X., 2019. An implementation of smart contracts by integrating BIM and blockchain. pp. 519–527. http://dx.doi.org/10.1007/978-3-030-32523-7_36.

Sinclair, D., 2013. RIBA Plan of Work 2013 Overview, URL https://www.ucl.ac.uk/estates/sites/estates/files/riba_plan_of_work_2013_-_overview.pdf.

Singh, A., Parizi, R., Han, M., Dehghantanha, A., Karimipour, H., Choo, K.-K.R., 2020. Public blockchains scalability: An examination of sharding and segregated witness. ISBN: 978-3-030-38180-6, pp. 203–232. http://dx.doi.org/10.1007/978-3-030-38181-3_11.

Srećković, M., Šibenik, G., Breitfuß, D., Preindl, T., Kastner, W., 2021. Analysis of design phase processes with BIM for blockchain implementation. In: ECPPM 2021–EWork and EBusiness in Architecture, Engineering and Construction. CRC Press, pp. 125–131.

Tao, X., Das, M., Liu, Y., Cheng, J., 2021. Distributed common data environment using blockchain and interplanetary file system for secure BIM-based collaborative design. Autom. Constr. 130, 103851. http://dx.doi.org/10.1016/j.autcon.2021.103851.

Turk, Žiga., Klinc, R., 2017. Potentials of blockchain technology for construction management. Procedia Eng. 196, 638–645. http://dx.doi.org/10.1016/j.proeng.2017.08.052.

Vinayak, M., Pal Singh Panesar, H.A., Santos, S.d., Thulasiram, R.K., Thulasiraman, P., Appadoo, S., 2018. Analyzing financial smart contracts for blockchain. In: 2018 IEEE International Conference on Internet of Things (IThings) and IEEE Green Computing and Communications (GreenCom) and IEEE Cyber, Physical and Social Computing (CPSCom) and IEEE Smart Data. SmartData, pp. 1701–1706. http://dx.doi.org/10.1109/Cybermatics_2018.2018.00284.

Vranken, H., 2017. Sustainability of bitcoin and blockchains. Curr. Opin. Environ. Sustain. 28, 1–9. http://dx.doi.org/10.1016/j.cosust.2017.04.011.

Xu, Y., Chong, H.-Y., Chi, M., 2022. Blockchain in the AECO industry: Current status, key topics, and future research agenda. Autom. Constr. 134, 104101. http://dx.doi.org/10.1016/j.autcon.2021.104101.

Xue, F., Lu, W., 2020. A semantic differential transaction approach to minimizing information redundancy for BIM and blockchain integration. Autom. Constr. 118, 103270. http://dx.doi.org/10.1016/j.autcon.2020.103270.

Zou, W., Lo, D., Kochhar, P.S., D Le, X.B., Xia, X., Feng, Y., Chen, Z., Xu, B., 2019. Smart contract development: Challenges and opportunities. IEEE Trans. Softw. Eng. PP, 1. http://dx.doi.org/10.1109/TSE.2019.2942301.