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CONCEPTUAL FRAMEWORK FOR DECENTRALISED INFORMATION MANAGEMENT ALONG THE ENTIRE LIFECYCLE OF A BUILT ASSET

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Abstract

The construction industry is characterised by a high level of fragmentation, inefficient collaboration and a lack of trust between project stakeholders. Issues due to the fragmented nature of the construction industry are extenuated from centralised Building Information Modelling approaches. Blockchain technology can help address information management issues by providing data traceability, transparency, and immutability. First, this paper reviews centralised and decentralised approaches to lifecycle information management. Second, a conceptual framework for decentralised information management workflow based on blockchain technology and the Inter-Planetary File System is proposed. Smart contracts can improve the information flow between different phases by providing more accountability.

Introduction

Many construction industry problems result from its high fragmentation and decentralisation, which occurs at three different levels (Riazi *et al.*, 2020). First, construction projects involve multiple parties, such as architects, engineers, contractors etc., who collaborate during the whole project life cycle. The construction industry in the UK and elsewhere comprises Small-Medium-Enterprises (SMEs)(Barton, 2020). In the US, more than 90% of all construction firms are SMEs with less than 20 employees (Eastman *et al.*, 2018). The geographical isolation of professionals causes numerous barriers to fast and effective communication, coordination and collaboration (Riazi *et al.*, 2020). Moreover, research on innovative technologies requires an up-front investment and involves risks that small construction companies usually can not take. Secondly, traditional construction project delivery practice is carried out sequentially, as an activity can only start after another one completes. Lifecycle phases such as design, construction, and operation and maintenance are distinct in traditional contracting practice (design-bid-build); this fragments information flow between the parties and causes a lack of coordination between different phases. Poor interactions might lead to aggressive behaviours as involved parties have no opportunity to build up trust and shared understanding (Riazi *et al.*, 2020). The third level of fragmentation occurs due to the unique nature of projects, as usually, each project involves a different set of stakeholders. Frequent changes in teams make it difficult to build tacit knowledge from project to project, slowing down innovation diffusion and hindering practical cooperation (Hall *et al.*, 2014).

The digital transformation of the Architecture, Construction, Engineering and Operations (AECO) industry is enabled due to advances in Building Information Modelling (BIM) (Eastman *et al.*, 2018; Mathews *et al.*, 2017). Effective use of BIM in construction projects improves information flows and leads to enhanced building management across the lifecycle (Eastman *et al.*, 2018). However, centralised BIM solutions are not suitable for the fragmented nature of the construction industry. Providing a trust-less technology for managing project data could help building trust among the stakeholders who in general do not trust each other (Das *et al.*, 2021a). Trust is vital in construction because of how much each stakeholder and each step of a project relies on the performance of others (Acker *et al.*, 2020). BIM-based collaboration raises concerns about data security, data ownership, legal implications and responsibility distribution in shared BIM models (Eastman *et al.*, 2018). Many authors claim that blockchain technology could provide a catalyst for BIM in reaching its full potential as it might provide a solution to the problem of trust (Mathews *et al.*, 2017; Tezel *et al.*, 2020). Blockchain features such as decentralisation, the immutability of decisions and files, and intellectual property protection can help tackle some of the centralised BIM implementation shortcomings (Dounas *et al.*, 2020b). A report from the Institute of Civil Engineers (Penzes, 2018) indicates that blockchain can tackle problems such as lack of accountability, transparency and efficiency in the construction industry. Maciel believes that blockchain-enabled BIM can act as a bridge between all stakeholders in BIM-based collaboration, leading to highly integrated workflows and closer and more transparent collaboration (Maciel, 2020).

This paper aims to investigate the problems of current centralised BIM-based information management workflows during a built asset's lifecycle and help understand how decentralised technologies can help overcome these problems. In particular, this paper focused on the following research questions: 1) Is the centralised BIM approach to information management suitable for the built asset lifecycle management? 2) How can blockchain technology facilitate the information management workflow across an asset's entire lifecycle?

First, this paper defines key terms surrounding Distributed Ledger Technologies and blockchain. Secondly, a short literature review about centralised and decentralised approaches to information and data management in the construction industry is presented. Afterwards, we propose a conceptual framework for decentralised information and data management workflow during the entire lifecycle of a built asset. In the end, we discuss the implications of the framework and the directions for future research.

Key terms

Blockchain technology

Blockchain is a Distributed Ledger Technology (DLT) and was first introduced in the white paper by Satoshi Nakamoto (2008) as a base for the world's first cryptocurrency named Bitcoin. DLT is a database of transactions stored in a network of multiple nodes simultaneously, making it decentralised and immutable. A highly resilient network protocol and consensus mechanism enable all network participants to interact with each other in a peer-to-peer manner without a need for intermediaries and a third party controlling the network. All interactions are cryptographically secured and added to an immutable record of transactions, which is a single source of truth (Perera *et al.*, 2020). The details about how blockchain functions were described extensively by other authors, such as Perera et al. (2020) and Mukherjee and Pradhan (2021).

One of the most fundamental and disruptive innovations enabled by blockchain is smart contract, which is a digital program requiring no middlemen to execute defined terms once pre-defined conditions are met (Mukherjee and Pradhan, 2021). A particular type of smart contract, which resembles a form of an organisation corporation working on a blockchain, is known as Decentralised Autonomous Organisation (DAOs). Unlike traditional organisations, they exist only in the blockchain and have no board of directors or headquarters (Kinnaird and Geipel, 2017). Smart contracts encode all decision mechanisms and consequent actions in the DAOs. They can be triggered based on data coming from IoT devices, allowing them to automatise various actions in smart environments (Hunhevicz and Hall, 2020).

Depending on their governance mechanism, there are three types of blockchain architectures: public, private and consortium blockchain. They differ depending on the access and permission level, and consensus mechanism used, leading to different scalability possibilities and environmental impact (Mukherjee and Pradhan, 2021).

Inter-planetary File System (IPFS)

Saving large files such as BIM models on a blockchain can be difficult and computationally expensive. The Inter-planetary File System (IPFS) was created to address this challenge in distributed applications (Dounas *et al.*, 2021). IPFS is "a peer-to-peer distributed file system that seeks to connect all computing devices with the same files system" (Benet, 2014). IPFS utilises some successful ideas of four other enabling technologies. It uses a routing system based on Distributed-Hash Tables (DHTs), a block exchange protocol inspired by BitTorrent, a version control system from Git and a naming system based on the self-certified filesystem (Benet, 2014). Each file stored on the IPFS is associated with a unique cryptographic hash generated by the SHA256 algorithm (Dounas *et al.*, 2021) called the content identifier (CID). The CID works as the "address" of the file, making it findable and addressable to other network members and giving them access for downloading (Tao *et al.*, 2021). Only concerned stakeholders receive the CID link to ensure the right access and permission control. IPFS, through its distributed nature increases reliability of data. Cryptographic hashing supports the immutability of stored files and version control. Replacing central data storage with distributed use of the IPFS could improve information flows in the construction industry as it offers faster and safer exchanges and enhances data protection (Darabseh and Martins, 2021).

Blockchain in the AECO industry

Our previous literature review (Jaskula and Papadonikolaki, 2021) provides an overview of blockchain applications for the construction industry. It suggests that DLT and smart contracts can benefit the entire lifecycle of a built asset. Blockchain applications such as triggering payments and contract deliverables, recording ownership, notarisation and synchronisation of documents, shared accounts and insurances, and a Decentralised Common Data Environment can be used during the whole lifecycle of a built asset. In the design phase, typical blockchain use cases include changes in BIM models, a record of ownership of digital components, automated code compliance checking and tendering process. In contrast, in the construction phase, it is mainly used to track supply chain logistics, verification of installation tasks and tracking of health and safety incidents. The provenance of products and materials used during the construction phase can be monitored throughout the Operation and Maintenance (O&M) phase using Material and Product Passports. In the O&M phase, there is also a high potential for blockchain-enabled records of maintenance and operation data and automated Building Maintenance Systems (Jaskula and Papadonikolaki, 2021).

Literature review

Information management standards

According to the ISO 19650 Standard, information exchange in construction projects should be facilitated by a Common Data Environment (CDE) for sharing and coordinating information, using open standards whenever possible, and clearly defining operating procedures to enable a consistent information exchange approach for all organisations involved. CDE is defined in the standard as "an agreed source of information for any given project or asset for collecting, managing, and disseminating each information container through a managed process". A CDE solution and related workflow should manage information during project delivery and asset management. Each file can be in one of the four states: work in progress (WIP), shared, published or archived. The transition from one state to another should be subject to approval and authorisation processes (BSI, 2021).

The information lifecycle in construction projects can be divided into two stages: the information delivery and the information operation phases. The former includes the data created from the project's initiation through the design and construction phases of a built asset and results in the generation of PIMs (Project Information Model). The latter consists of data from the operation and maintenance (O&M) phase of a built asset and generated AIM (Asset Information Model) (BSI, 2021). The handover process between the two stages should be established using Construction Operations Building information exchange (COBie), a non-proprietary format using a conventional spreadsheet (Eastman *et al.*, 2018).

A CDE is necessary for the entire lifecycle of a built asset. It facilitates continuous collaboration between all project participants and ideally works as a single source of truth for all project information. Therefore CDE must uphold data security, quality, and integrity standards secured by blockchain (Nawari and Ravindran, 2019).

A CDE is usually a cloud-based repository where all stakeholders can store and access project data. According to the BIM survey (NBS, 2020), Viewpoint/4projects is the most popular technology solution for a CDE, used by half of the respondents, followed by Autodesk 360, with 39% of respondents using it. A significant number of the respondents are using Dropbox (38%) and Microsoft SharePoint (36%) as a CDE, and another 36% used Aconex/Conject (NBS, 2020). It is noticeable that general-purpose file-based document management systems, like Google Drive, Microsoft SharePoint and OneDrive, Dropbox are widely used as a CDE (NBS, 2020). The fact that participants have chosen more than one answer indicates that many stakeholders are using various cloud solutions simultaneously (NBS, 2020). However, utilising multiple repositories simultaneously can lead to data duplication, data loss, and loss of integrity. Moreover, cloud file hosting services such as Dropbox or Google Drive are not designed to be a technological solution for a CDE. They lack the required functionality and security, like object-level versioning, or integration of federated BIM models (Das *et al.*, 2021b).

Centralised data management

Collaboration in a BIM-based environment raises many concerns, such as low-security levels and a threat of data leakage, which is a significant issue in public buildings and infrastructure projects. Another concern is data ownership, legal implications, and responsibility distribution in shared BIM models (Eastman *et al.*, 2018). Currently used cloud platforms are vulnerable to security risks such as data loss, denial of data access, and partial control over sensitive data. Entrusting all project data to a central entity only magnifies the problem of lack of trust between project stakeholders. Existing centralised systems consolidating all project documents on a physical or cloud-based platform are not suitable for the fragmented construction industry (Das *et al.*, 2021a).

Das et al. (2021b) examined commonly used technological solutions for BIM collaboration platforms. They classified them into 3 Levels of BIM Security, considering the security of data, network and systems, data ownership, data sharing, data integrity and information flow. The first level, which presents unstructured file servers, includes cloud file repositories such as Dropbox and Samba file servers. This solution is prevalent among small and medium-sized construction companies due to its low cost and ease of implementation. However, unstructured file servers do not provide the necessary functionality and security levels as they do not facilitate data privacy and create a single point of failure. Level 2 includes structured file servers, which maintain the interrelations among files, unlike unstructured file servers. The NBS BIM Toolkit is an example of a structured file server to store BIM files and project documents. The third BIM security level includes structured-data servers such as Autodesk 360. They facilitate the storage and exchange of BIM data and related project information at the object level based on a pre-defined data model. They provide high data granularity and facilitate partial access and modification of BIM models more effectively. However, collaborative BIM platforms such as Autodesk BIM 360 rely on cloud service providers that are not tailored to the requirements of BIM security, such as secure data divisibility and data ownership at the object level (Das *et al.*, 2021b).

Parn et al. (2019) provided an extensive review of possible cyber threats confronting the digital built environment and highlighted vulnerabilities of the current centralised CDE approach. The whole lifecycle of an asset, including its operation, might be endangered by possible data manipulation that is hard to detect in a centralised database and may result in unrecoverable data damage (Tao *et al.*, 2021). Security defences, such as antivirus or firewalls, are not hindering internal data manipulation. Project participants themselves can abuse their authorised access to a CDE and tamper with data for their advantage (Das *et al.*, 2021a).

Decentralised data management

Both BIM methodology and blockchain rely on the idea of serving as a single source of truth for all project participants (Di Giuda *et al.*, 2020). One of the biggest strengths of blockchain is the high level of security, making it a suitable solution as an underlying technology for BIM exchange servers (Das *et al.*, 2021b). Blockchain enables an immutable record of BIM model changes and an immutable record of ownership of a model or a digital component (Kinnaird and Geipel, 2017; Penzes, 2018; Turk and Klinc, 2017). Thanks to timestamping of transactions and a tamper-proof guarantee, the record is transparent and easily traceable. A cryptographically secure digital signature ensures data provenance and tracking metadata, such as timestamps or author information. Blockchain ensures the integrity and accountability of information and removes the need of a central trusted authority (Turk and Klinc, 2017). Parn and Edwards suggest that blockchain would be a suitable solution for storing sensitive digital infrastructure data with high-security and privacy requirements. Blockchain resistance to cyber attacks would fortify the security of built assets managed digitally in the CDE environment (Parn and Edwards, 2019).

A set of smart contracts on the Ethereum blockchain can store the hashes of saved files, and through this, a record of changes can be stored on a public and open blockchain. However, one of the biggest challenges of integrating BIM with blockchain technology is information redundancy, as BIM files are known for their massive data volume. Several authors have attempted to solve this problem using different methods. One approach is to record only the differences between different versions of a model on the blockchain (Xue and Lu, 2020), and the other is to store only the BIM files' hashing signatures on a blockchain (Zheng *et al.*, 2019). Dounas *et al.* (2020a) proposed a new alternative method, storing whole BIM files in the IPFS storage.

Das et al. (2021a) proposed a framework for Distributed Construction Document Management System, which deploys smart contracts for documents approval workflows such as design review processes or information requests. Darabseh and Martins (2021) and Erri Pradeep et al. (2020) also propose IPFS to enhance data management in construction, as it secures data reliability and file immutability and security. The authors used IPFS storage to facilitate data integrity and decentralisation.

A concept of decentralised CDE (DCDE) based on the blockchain instead of traditional central cloud-based solutions was mentioned firstly by Kinnaird and Geipel (2017) and by Parn and Edwards (2019). Tao et al. (2021) proposed a framework for distributed CDE for the design phase based on the Hyperledger Fabric blockchain. The authors chose this platform because it protects data privacy by allowing only authorised project members to participate in the network, thanks to its modularity and extensible open-source character. The authors used the IPFS storage system. IPFS could offer a solution to data privacy and security (Li and Kassem, 2021). Integrating blockchain and IPFS solves the problem of storing large-sized design files and supports a secure BIM-based collaborative design process (Tao *et al.*, 2021).

Research method

This research paper focuses on developing a conceptual framework based on the outcomes of the literature review which outlines the problems and limitations of centralised BIM and suggests ways that blockchain technology can improve the workflows in lifecycle information management. To address identified problems, we propose a framework for decentralised information management along the whole lifecycle of a built asset (Figure 1). The integration of blockchain records and IPFS storage is currently the most promising solution for information management in construction projects, as suggested in the literature review.

United Kingdom is one of the most advanced countries in BIM adoption (Eastman *et al.*, 2018). We decided to base our framework on the RIBA Plan of Work, as it is widely used for BIM-based lifecycle information management. The Plan of Work 2020 (RIBA, 2020), created by the UK Royal Institute of British Architects (RIBA), distinguishes eight lifecycle stages involving different stakeholders and actions. For our framework, we merged some of the RIBA stages and distinguished the following six stages: 1) Preparation (including Strategic definition and preparation and briefing), 2) Design (including Concept design, Spatial coordination and Technical design), 3) Construction (including Manufacturing and construction), 4) Handover, 5) Operation and Maintenance (Use), and 6) Termination phase (not a part of RIBA Plan). The framework can be used for traditional procurement (design-bid-build) and Design-Build routes. Different colours (red – traditional, green – Design-Build) present actions specific for each route. The framework involves multiple stakeholders directly involved in the project, such as Clients, Architects, Engineers, etc. and stakeholders not directly involved in the collaboration process but influencing the project outcomes (Sub-contractors and Authorities). A UML sequence diagram was utilised to represent the sequentiality of events in the built asset's life cycle.

Framework proposal

The framework is based on the continuous use of a decentralised CDE comprising two elements: a blockchain to record transactions and IPFS for storing geometrical and non-geometrical data. Prototypes from Dounas *et al.* (2020b) and Tao et al.(2021) proved that linking IPFS with private and public blockchain platforms is feasible for BIM-based collaboration. IPFS can be used for the low-frequency file-based data exchanges, while high-frequency transactions are recorded on the blockchain. The CID of files stored in IPFS should be recorded on the blockchain to provide data integrity.

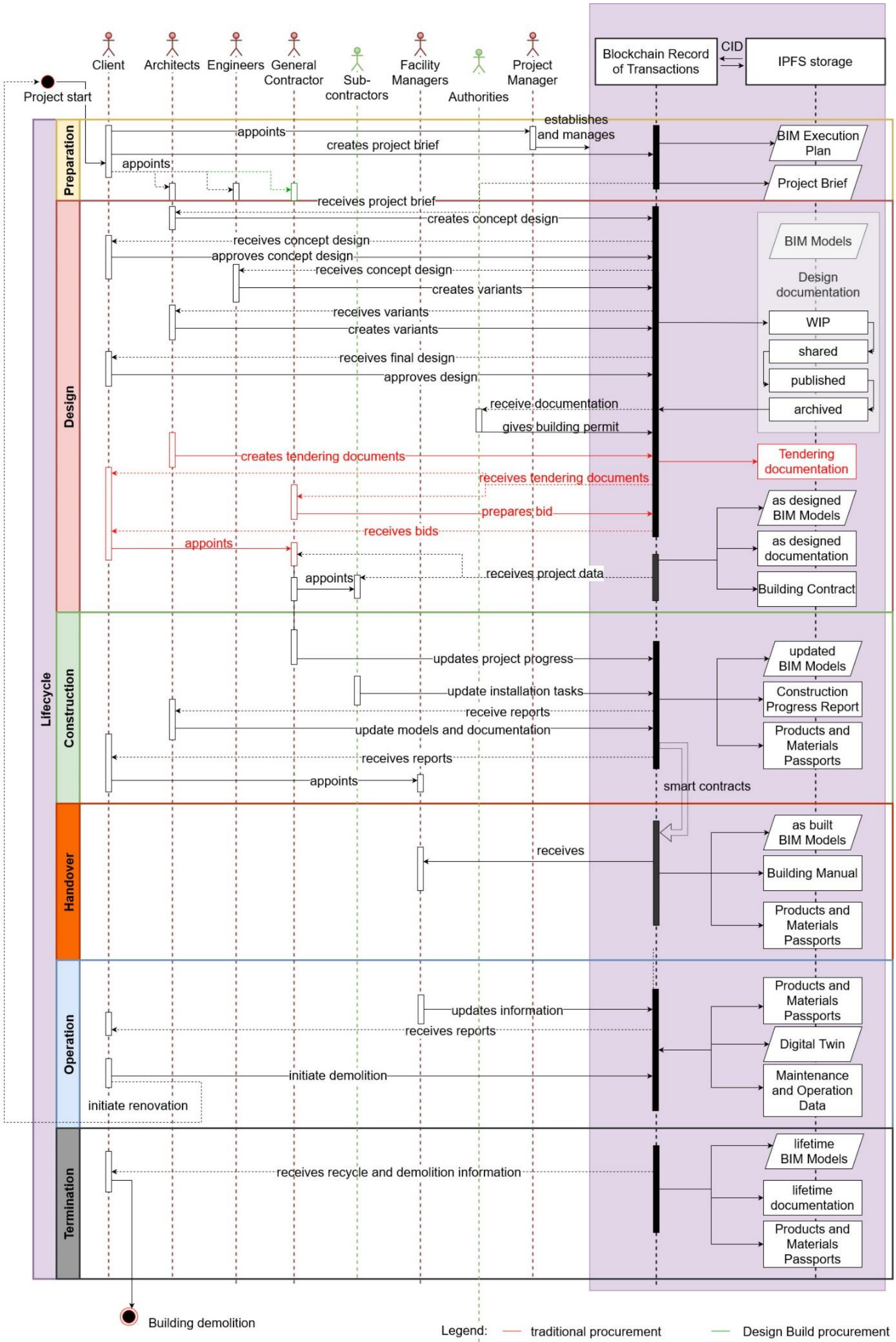

Figure 1 Conceptual framework of a decentralized information management workflow. Red color refers to the traditional procurement route and green color to the Design Build procurement route.

Preparation phase

The client prepares Project Brief in the preparation phase, including the Client Requirements and Project Budget. The client appoints the design team comprising architects and engineers and, in the case of Design-Build procurement, the General Contractor team. A project manager who can be a part of the design team or can be appointed externally has the task to establish the Common Data Environment, which will be used along the entire lifecycle of a built asset. Once a CDE is established and all project participants receive access, the Project Brief might be uploaded and shared with all participants.

Design phase

After Architect and Engineer Teams are appointed and have received Project Brief documents, they can start to work on developing design concepts. The design phase is a process of continuous development of design variants where collaboration between stakeholders is essential. All transactions between the stakeholders should be recorded on the blockchain, while all BIM models should be stored on the IPFS storage. The files can be stored in one of the four containers corresponding to ISO 19650 states namely "work in progress", "shared", "published" or "archived". The file hashes can be distributed only with concerned members to ensure the data protection (Darabseh and Martins, 2021). When the client approves the final design, smart contract is triggered to change the status of the file from "shared" to "published" (Tao *et al.*, 2021). A link to the final documentation can be shared with the authorities to obtain a permit to build. In the traditional procurement, tendering documents are prepared simultaneously. The client appoints a general contractor and subcontractors through the tendering process to deliver the building per the Construction Programme agreed in the Building Contract stored in the blockchain. At the end of the Design phase, a final set of as-designed BIM models and documentation is established.

Construction phase

In the Construction phase, the General Contractor supervises the progress of the construction. The contractor updates the project progress on the blockchain, using subcontractors' information about completed installation tasks. Optionally, project progress could also be attested using external information obtained from sensors, cameras or scanning devices. In case of changes to the project, the architect team should update the BIM models stored on the IPFS. Information about installed products and materials should also be uploaded to the IPFS to create Material and Product Passports.

Handover

At the end of the construction phase, the handover of the complete documentation of the built asset, including the as-built BIM model, Product and Material Passports, and Building Manual, could be automated by implementing smart contracts. The client appoints a Facility Management team that receives access to the CDE, and therefore, the handover can be completed.

Operation and Maintenance phase

After the handover, the Facility Management (FM) team has all information required to manage and operate the building. During the O&M phase, the FM team should record details on building operations and maintenance on the blockchain. Product and Materials Passports stored on the IPFS can be updated according to the usage of elements and conducted repairs. Incorporating data coming from IoT sensors could be facilitated by smart contracts, which can trigger some repeatable maintenance actions. The client always has access to the O&M data records and uses these to make decisions about necessary renovations or demolition of the building.

Termination phase

Assuming a correct use of CDE in previous stages, a data record from the whole lifecycle of an asset and Product and Material Passports provide knowledge about every element of a building, allowing sustainable reuse and recycling of materials after the demolition of a building.

Discussion

The single source of truth described by the ISO 19650 standard is difficult to implement in practice, as most projects rely on multiple sources of information. Currently used centralised CDE solutions are not corresponding with the needs of the highly fragmented construction industry. The current form of a centralised CDE needs to be re-evaluated, with other more decentralised solutions investigated.

Recording all information in a blockchain-based DCDE might be a solution to create a single source of truth during the entire lifecycle of a built asset. Currently developed blockchain applications for the AECO industry often focus only on one application type and one lifecycle phase (Jaskula and Papadonikolaki, 2021; Li and Kassem, 2021). Consequently, the potential of blockchain to enhance the continuity of the information flow during the whole lifecycle is not fully explored. A DCDE should integrate data management throughout the entire lifecycle of an asset, and therefore a smooth handover between the phases could be established. For this reason, we propose a conceptual framework for decentralised information management along the entire lifecycle of a built asset. In each phase, transactions between stakeholders are recorded in the blockchain and files are stored on the linked IPFS storage. The framework integrates the ideas of other authors, such as a record of changes to BIM models, document management systems, tracking of construction progress, Material and Product Passports, records of O&M data and an automated Building Maintenance System. Integrating these ideas into a single framework allows to fully exploit the benefits of blockchain technology to establish a reliable single source of truth for project data which provides a better accountability of information along built asset lifecycle.

The socio-technical framework for implementation of DLT in construction proposed by Li and Kassem (2021) encompasses four dimensions: technology, process, policy and society. Implementing technological systems such as blockchain is not happening in a vacuum and must overcome many challenges. To ensure its success and realise all the benefits, the whole ecosystem present in the industry needs to adapt. It is essential to investigate the integration or disruption of the current landscape of processes, standards, and technologies adopted within the construction sector (Li and Kassem, 2021). Implementing the proposed framework would also require a change of currently used standards such as COBie and changes in presently used software and tools. It is important to make the change as smooth as possible for all the stakeholders and provide an easy-to-use platform.

As it is a conceptual framework, the next step is to investigate how the transactions between all the stakeholders will be recorded on the blockchain and the technological solution to record transactions from different software. Also, the integration of data coming from IoT devices should be further investigated in the construction and O&M phase. Proposed solutions for blockchain-based CDE from (Tao *et al.*, 2021) proved that saving transactions between stakeholders in the design phase is feasible. As developing a decentralised CDE for other lifecycle phases was not investigated, it is necessary to develop a proof of concept or a tool prototype, especially for the construction and O&M phases.

Conclusion

This paper has outlined current practices for information management in BIM-based collaboration, discussed the limitations of centralised BIM solutions and presented the recent developments in decentralised information management solutions. It is one of the first studies to propose implementing blockchain technology for decentralised information management during the entire lifecycle of a built asset and not only for a specific use case or lifecycle phase. The framework is based on the continuous use of a decentralised CDE comprising blockchain records of transactions and linked IPFS data storage. The next step of the research should be a development of a prototype and a case study to validate the framework's usability.

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