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Blockchain-Based Decentralized Common Data Environment: User Requirements and Conceptual Framework

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Abstract: A common data environment (CDE) is defined as a single source of truth for all project information that facilitates continuous collaboration between stakeholders. In practice, multiple CDEs are used simultaneously, leading to a lack of data integrity, traceability, and transparency. Moreover, current centralized cloud-based CDEs are vulnerable to security risks such as data manipulation, which magnifies the lack of trust among project stakeholders. Previous studies proposing blockchain for information management focused on narrow use cases and did not encompass the whole life cycle of a built asset. This work aims to develop a framework for decentralized information management concerning all life cycle phases. First, we identify the users' needs for a CDE using desk research and an empirical approach, including semistructured interviews with industry experts. It is found that the top user requirement is integrating data scattered across multiple CDEs along the built asset's life cycle in a single source of truth. A CDE should provide an accountable and transparent record of the entire project history, integrating data from various tools utilized during the life cycle. In the final step, we propose a conceptual framework for a blockchain-based CDE where transactions from various tools used along the entire life cycle of a built asset are recorded on a blockchain linked with Inter-Planetary File Storage (IPFS) to increase the security of the files. Three illustrative use-case scenarios demonstrate the framework's applicability in the design, construction, and operation phases. The utilization of blockchain technology ensures an immutable, independent, and reliable record of all transactions, offering a comprehensive and tamper-proof history. This approach addresses gaps in previous studies and lays the foundation for establishing trustworthy product and material passports. **DOI: 10.1061/JCEMD4.COENG-14852.** *© 2025 American Society of Civil Engineers.*

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Introduction

The digital transformation of the architecture, construction, engineering, and operations (AECO) industry is enabled in part by advances in building information modeling (BIM) (Mathews et al. 2017; Sacks et al. 2018). Effective use of BIM can improve information flows and lead to improved collaboration and outcomes across the life cycle (Sacks et al. 2018). A common data environment (CDE) in BIM-based collaboration can support information management workflows, as the ISO 19650 international standard recommends (BSI 2021). However, using BIM raises concerns about the data security, ownership, legal implications, and responsibility distribution of shared BIM models (Sacks et al. 2018).

Centralized BIM solutions do not align well with the AECO industry structure due to the high fragmentation occurring at three levels (Riazi et al. 2020). First, construction projects involve multiple parties (e.g., architects, engineers, contractors, and so on) collaborating during the project life cycle. However, practitioners' geographical isolation and professional fragmentation cause numerous barriers to fast and effective communication, coordination, and collaboration (Riazi et al. 2020). For example, the UK and US construction industries mainly comprise small-medium enterprises (SMEs) (Barton 2020; Sacks et al. 2018). Research and adoption of innovative technologies in production workflows require up-front investments and involve too high risks for SMEs (Vidalakis et al. 2019).

Secondly, standard construction project delivery is carried out sequentially (Hall et al. 2014). Life cycle phases such as design, construction, and operation and maintenance (O&M) are partitioned in traditional contracting practice (design–bid–build); this disrupts information flow between the parties and causes a lack of coordination across phases. Poor interactions might lead to poor communication that might hamper the development of trust and shared understanding between disjoint entities (Riazi et al. 2020). The third level of fragmentation occurs due to the unique nature of projects—each project usually involves different stakeholders. Frequent team changes and tacit knowledge that are not adequately captured can hinder feeding forward lessons learned to new projects (Hall et al. 2014).

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Digital collaboration in BIM-based environments raises issues covering diverse domains such as data ownership, legal and contractual liability, data provenance and responsibility distribution, and data security and protection (Sacks et al. 2018). Data such as financial information or clients' personal information are in danger of inappropriate sharing or being lost leading to serious financial or reputational consequences (Das et al. 2021a). Cloud solutions are vulnerable to security risks, including unauthorized access, sensitive data loss, denial of service, or other cyber-attacks (Check Point 2022). Existing centralized systems consolidating all project documents on one cloud-based platform might additionally magnify the lack of trust among project stakeholders; security defenses, such as antivirus or firewalls, are not hindering internal data manipulation. Project participants themselves can abuse their authorized access to a CDE and tamper with data for their advantage (Das et al. 2021b). To ensure that data are not tampered with by stakeholders or a malicious third party, a trusted third party is necessary, which in some CDEs could be the software providers themselves (Oracle 2022).

Blockchain technology removes the need for a third trusted party to validate transactions between mutually distrustful participants (Brotsis et al. 2020; Xu et al. 2017). More importantly, blockchain highlights a paradigm of decentralized collaboration and consensus building that might align with the way the construction industry operates better than centralized solutions. Providing a trustless and democratic technology for managing project data could help build trust among construction project stakeholders (Das et al. 2021b). Decentralization, data immutability, and intellectual property protection are blockchain features that can help tackle some of the centralized BIM implementation shortcomings (Dounas et al. 2020b).

The potential of using blockchain for developing a CDE or a BIM collaboration platform was explored in a few previous studies. Hijazi et al. (2021) investigated the rationale for integrating blockchain and BIM for construction supply chain data delivery based on focus groups with industry stakeholders. In another study, Hijazi et al. (2023) developed a prototype of a single source of truth based on blockchain to support supply chain data delivery for handover. Tao et al. (2021) developed a distributed CDE for the design stage based on blockchain and the Inter-Planetary File System (IPFS). However, the proposals from previous studies are limited to a single life cycle phase or a narrow use case.

Moreover, none of the previous studies investigated what stakeholders are currently using, what challenges they have with current tools, and how the tools could be improved. This is a significant gap because proposing any type of new software or product should be preceded by understanding the users' needs toward the proposed tool. Understanding user requirements is a crucial component of systems design and is essential to the success of a support system (Shen et al. 2004). Therefore, this study aims to define the user requirements for a CDE platform and help understand how decentralized technologies can aid in fulfilling these requirements and in overcoming current challenges in information management during the whole life cycle of a built asset.

Notably, this paper focuses on the following research questions (RQs):

- RQ1: What are the stakeholder requirements toward a CDE platform and the shortcomings of existing centralized approaches?
- RQ2: How can blockchain technology facilitate CDE-based information management across an asset's entire life cycle?

This paper is structured as follows. First, we explain the research background, including ISO 19650 definition, challenges to CDE implementation, and blockchain technology principles. Secondly, the research methods are explained in detail. Third, a literature review of CDE functionalities and requirements is presented. Afterward, the results of semistructured interviews with industry professionals are presented followed by the synthesis of the results. Subsequently, a conceptual framework for decentralized information and data management workflow during the entire life cycle of a built asset is proposed. Finally, we discuss the potential benefits and limitations of implementing blockchain in a CDE workflow, the implications of the framework, and the directions for future research.

Research Background

Key Terms and Definitions

According to ISO19650 (BSI 2021), a CDE should be used to share and coordinate information in construction projects, wherever feasible utilizing open standards, and precisely describing operational processes to ensure a consistent information exchange for all organizations participating. A 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" (BSI 2021, p. 5). A CDE consists of a "CDE solution" and a "CDE workflow" that organize the information flow during an asset's entire life span across four information container stages (BIM Dictionary 2020). Each file can be in one of the following states: work in progress (WIP), shared, published, or archived; the transition from one state to another should be subject to approval and authorization processes (BSI 2021).

WIP is used for the initial development stage for sharing information only among team members in one stakeholder group, which is not available to other project stakeholders. After approval, the information can move to the shared state, where other task teams or the client can view the information. After review and authorization processes take place, the final version of information can move to the published state and be used in the construction and asset management phase. Additionally, the archived state is used to provide "a journal of all information container transactions and an audit trail of their development" (BSI 2021). The CDE solution is usually a server-based or cloud-based technology with database management, transmittal, issue tracking, and related capabilities that support the CDE workflow (BIM Dictionary 2020). According to a 2020 BIM survey (NBS 2020), Viewpoint/4projects is the most popular CDE technology solution, followed by Autodesk 360 and Aconex (NBS 2020). Survey results indicated that practitioners often use general-purpose file-based document management systems such as Dropbox or SharePoint in place of a fully featured CDE (NBS 2020).

The ISO 19650 standard distinguishes three stages of maturity of analogue and digital information management, which encompasses four layers: business, information, technology, and standards. Regarding the technology layer, a CDE in Stages 1 and 2 is still seen as a file-based solution, whereas in Stage 3, it is foreseen as a query-based solution. The information layer advances from structured and unstructured data in Stage 1 to federated information models in Stage 2 and to object-based servers in Stage 3 (BSI 2021).

In 2019, the DIN SPEC 91391 specification was published to complement ISO 19650 and specify functional levels of CDEs in more detail (DIN 2019). It includes a list of 209 functions that a CDE solution should have, including 36 that are optional functions (DIN 2019).

To more accurately describe what a CDE is beyond the generic definition provided by ISO 19650, Bedoiseau et al. (2022) developed a holistic CDE analysis framework with four levels of development in four areas, namely, documents, coordination, communication, and BIM production. In their framework, Level 0 is equivalent to the pre-CDE level, where there is no platform in place and document management is done manually often with the use of paper-based copies. Level 1 is a minimum CDE solution complying with the ISO standard and can be seen as equal to electronic document management (EDM) solutions.

In Level 2 CDE, BIM integration should be provided enabling multidisciplinary coordination and clash detection. The most advanced Level 3 of CDE should be centered around a single multidisciplinary BIM model where all documentation of the project is integrated, enabling a synchronous collaboration on the model (Bedoiseau et al. 2022). Das et al. (2021a) investigated the aspect of security in collaborative BIM platforms and distinguished three levels of BIM security, considering the security of data, network and systems, data ownership, data sharing, data integrity, and information flow. They distinguished unstructured file servers, structured file servers, and structured database servers (Das et al. 2021a).

The classifications from Das et al. (2021a) and Bedoiseau et al. (2022) did not consider the life span of data in construction projects. The information life cycle in construction projects can be divided into two stages: information delivery and information operation (BSI 2021). A CDE solution and its related workflow should manage information during project delivery and asset management (BSI 2021). Therefore, a comprehensive framework was previously proposed to analyze the development of CDE platforms (Jaskula et al. 2023). Features mentioned by Bedoiseau et al. (2022), such as documents, coordination, and communication, were grouped into one axis related to document management. BIM integration is an area independent of document management functionalities and is a critical aspect of CDEs; therefore, it is distinguished as the second axis. The security of CDE highlighted by Das et al. (2021a) was included in the framework as the third axis of CDE development. The last axis corresponds to the life cycle functionalities, which enable the use of CDE in different life cycle phases of a built asset (Jaskula et al. 2023).

Information Management Challenges

Currently, construction projects rely on centralized CDEs to manage information. These centralized systems serve as single points of access for project data, facilitating collaboration among stakeholders (Patacas et al. 2020). However, centralized CDEs have significant limitations. They often create data silos, where information is isolated within specific tools or departments (Soman and Whyte 2020). This fragmentation hinders seamless data integration across the project life cycle. Centralized CDEs are also vulnerable to security threats such as data breaches and unauthorized access (Turk et al. 2022). A single point of failure can compromise the entire system, leading to a loss of trust among stakeholders. Furthermore, centralized control can lead to a lack of transparency because stakeholders may not have equal access to project data. This can result in discrepancies and conflicts in project information (Das et al. 2021a).

Jaskula et al. (2024) analyzed the challenges surrounding the implementation of CDE tools for information management in practice. The results indicated that the most common challenge in using a CDE-based approach is the use of multiple sources of information instead of one single source of truth. Throughout the interviews, the participants reported that there is no single common data environment for all project data in the current practice, but rather multiple sources of information unconnected to each other (Fig. 1). During the design phase, solutions like Autodesk 360 or Aconex are used to manage BIM data, and Viewpoint4Project might be used to store documents and drawings for signing off. During O&M, different tools are used, including computer-aided facility management (CAFM) systems such as Concept Evolution, Autodesk Ops, and building management system (BMS) such as Cylon. Another tool, Springboard, can be used to hand over information between the construction and O&M phases. Some professionals also mentioned using simple cloud-based repositories such as Microsoft Sharepoint.

The various tools used in each stage can cause significant data integrity problems. The handover of information from BIM-based CDEs to CAFM systems often includes a manual information transfer about all the assets. Some of the interviewed professionals reported using additional tools specifically designed to facilitate the handover process, such as Springboard or eDocs; however, they still require a manual transfer of information to those tools. Typically postponed until the completion of construction, the handover process of design, construction, and O&M is highly unstructured, labor-intensive, and prone to errors (Patacas et al. 2020). In some cases, the handover process might take months or years when single subcontractors finish their work early and need to hand over their information at that time (Jaskula et al. 2024).

Poor communication between preconstruction and postconstruction CDEs complicates the process of uploading extensive information, such as BIM files, to a new system. It might become even more complex if clients do not use a proper CAFM but instead store their data in simple cloud storage. Information loss is common during data transfer between systems, making tracking transactions nearly impossible. This undermines trust in data accuracy, causing issues in traceability, integrity, and accountability (Jaskula et al. 2024).

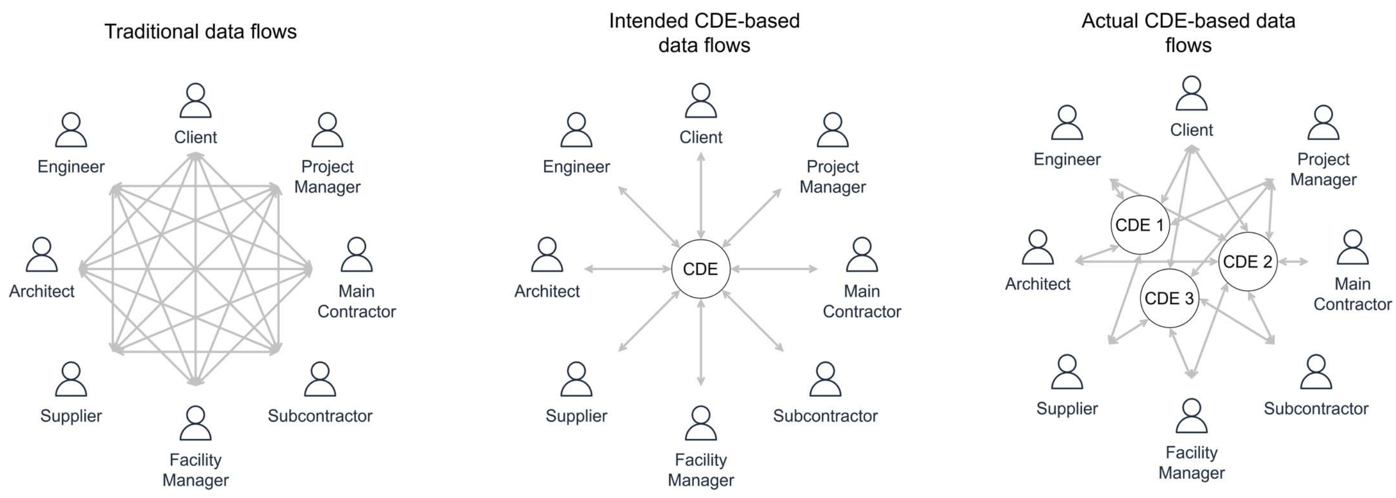

Fig. 1. Comparison of information management approaches in construction.

Decentralized Information Management

There are three types of file-system architecture: centralized systems, decentralized systems, and distributed systems. In centralized systems there is only one server node managing and controlling the data and all other nodes are client nodes connected to the server. In decentralized systems, there might be multiple server nodes, which means that in case of a failure of one of them, not all the data are lost. In distributed systems, there is no server node controlling the network, and all of the nodes are equal. Even if one of the nodes fails, the network stays undamaged (Darabseh and Martins 2021).

Decentralized information management refers to the process of managing data without relying on a single central authority. A decentralized approach mitigates risks associated with centralized systems, such as data manipulation and security breaches. In construction, this approach enables seamless data exchange by decoupling information from proprietary applications and fostering interoperability. Technologies such as blockchain ensure tamper-proof record-keeping, and distributed storage solutions prevent data loss. Linked Data, for example, allows different BIM systems to connect and share structured information across disciplines without requiring a central repository, making digital collaboration more accessible, particularly for smaller firms. By reducing dependence on centralized CDEs, decentralized information management enhances data sovereignty and trust among stakeholders (Werbrouck et al. 2019).

Blockchain is a distributed ledger technology (DLT), which is a database of transactions stored in a distributed network, with no need for a central authority to control the network (Xu et al. 2017). Transactions are grouped into blocks, with each block including a hash to the previous block, forming a chain of blocks, i.e., the blockchain (Mukherjee and Pradhan 2021). Accepting a new block depends on a consensus mechanism that varies among blockchain implementations. The system is designed to make it extremely difficult to tamper with any of the transactions on the blockchain because information in all succeeding blocks on every network node would have to be changed (Mukherjee and Pradhan 2021). A highly resilient network protocol and consensus mechanism can enable all network participants to interact with each other in a peer-to-peer manner (Hunhevicz and Hall 2020), with records of the block stored at multiple locations.

Additionally, all communications are cryptographically secured. The use of asymmetric encryption methods and state-of-the-art public-private key asymmetric cryptographic methods contribute to an immutable transaction record, thus becoming a single source of truth (Perera et al. 2020). Blockchain solves the double-spending problem, creating a new paradigm of data organization and enabling value transfers over the internet (Swan 2015). It has already impacted banking, finance, insurance, health, and education and may potentially transform the AECO industry (Kim et al. 2020; Nguyen et al. 2019).

Blockchain in Construction

Blockchain technology offers high transparency, traceability, and version control, serving as a reliable historical record-keeping system (Li and Kassem 2021). It is often proposed to enable tracking material and product provenance in construction. Each component or material used in the project can be registered with a unique ID on the blockchain platform, and in this way, create a possibility for digital identification, often called material and product passports. A material passport is a digitally recorded data set that documents an object's characteristics, location, history, and ownership status, with varying levels of detail based on its intended use (Talla and McIlwaine 2022). These passports enable tracking of each component from production through the supply chain and its installation until it is reused or recycled (Kinnaird and Geipel 2017).

Material passports typically include details such as physical and chemical properties, safety data sheets, bills of materials (BOM), logistics, disassembly instructions, and recyclability potential. Their creation involves multiple stakeholders across the supply chain, and notable databases facilitating their use include Madaster and Buildings as Material Banks (BAMB) (Hoosain et al. 2020). Recording them on the blockchain could ensure their integrity and accessibility throughout the asset's life cycle. By maintaining an accurate and transparent record of information, product and material passports support sustainable building practices and facilitate compliance with regulatory requirements (Li and Wang 2021).

Combining the decentralization of data records with cryptographic methods provides an exceptionally high level of security for blockchain and makes it a suitable solution as an underlying technology for BIM exchange servers (Das et al. 2021a). Blockchain enables an immutable record of BIM model changes and ownership of models or digital components (Kinnaird and Geipel 2017; Penzes 2018; Turk and Klinc 2017). The record is transparent and easily traceable thanks to transaction time-stamping and a tamper-proof guarantee (Hunhevicz and Hall 2020). A cryptographically secure digital signature ensures data provenance and tracking metadata, such as time-stamps or author information, ensuring information integrity and accountability (Turk and Klinc 2017). Blockchain-enabled BIM can act as a bridge among all stakeholders, leading to highly integrated workflows and closer and more transparent collaboration (Maciel 2020).

One of the biggest challenges of integrating BIM with blockchain is information redundancy because BIM files are known for their massive data volume (Das et al. 2021a). The need for cryptographic hashes and storage limitations make it impractical to store a record of object-level changes on the blockchain. Rather, it is more sensible to keep the hash of changes, which can be directly linked through the one-way hash function to the actual changes themselves (which can be stored somewhere else) (Xue and Lu 2020). This way, traditional cloud-based repositories could be still used because any attempt at data tampering would be detected through the blockchain.

An alternative to centralized repositories would be to store BIM files in distributed databases such as IPFS (Dounas et al. 2020a). IPFS is "a peer-to-peer distributed file system that seeks to connect all computing devices with the same system of files" (Benet 2014, p. 1). It was introduced as a new platform for sharing and versioning a large amount of data and writing and deploying applications, which could evolve into a new decentralized Internet infrastructure and replace the current Web.

IPFS utilizes some parts of four other technologies: distributed-hash tables (DHTs), BitTorrent, Git, and self-certified file system (Benet 2014). Each file stored on the IPFS is associated with a unique cryptographic hash value called content identifier (CID); CID works as the file's address or hyperlink, which can be sent to other network members to give them access for downloading (Tao et al. 2021). The CID is also evidence of a file's integrity because it would alter if the file's content were modified. The distribution of data protects it against any manipulation by the central entity or malicious agents (Tao et al. 2021). Decentralized systems make it difficult to collect all of an entity's data in one location, making IPFS nodes secure places to store sensitive data. When contrasted with cloud infrastructure, the IPFS design provides advantages in terms of safeguarding confidential information from malicious actors and any potential beneficiaries for whom they may be collecting it (Axel 2022).

IPFS increases the reliability and immutability of stored files and provides a unique file versioning system, providing faster and safer exchanges and improving data protection (Darabseh and Martins 2021). However, because IPFS is designed as a public network, it might raise questions about the privacy aspects of stored data. To solve this problem, various encryption methods can be used that ensure the privacy of the content and prevent any malicious party from decrypting the retrieved data (IPFS 2022). Few studies in the construction industry domain, such as that of Darabesh and Martins (2021), have investigated the use of IPFS to enhance data management in construction. Das et al. (2021a) proposed a framework for a distributed construction document management system, which deploys smart contracts for documents' approval workflows, such as design review processes or information requests. Another study from Tao et al. (2021) presented a distributed CDE based on blockchain and IPFS for secure BIM-based collaborative design.

Research Gaps and Objectives

Previous research studies on blockchain-based CDEs focused on providing a technological solution in the form of a data model (Hijazi et al. 2022), smart contracts (Ciotta et al. 2021), or a prototype (Das et al. 2021b; Hijazi et al. 2023; Tao et al. 2021). Although these approaches showed that blockchain is a feasible solution to be integrated with BIM and as a method to record transactions between CDEs, they were limited to narrow use cases, such as recording document metadata (Ciotta et al. 2021; Das et al. 2021b), handover information (Hijazi et al. 2022), BIM changes (Das et al. 2021a), or design approvals (Das et al. 2021b; Tao et al. 2021).

Studies by Das et al. (2021a) and Tao et al. (2021) proposed solutions targeting the design phase, whereas Hijazi et al. (2021) investigated using blockchain technology to establish a single source of truth in the construction supply chain and facilitate more efficient construction information handover. Data sharing platforms in O&M phase were rarely investigated by researchers in context of blockchain integration. Notably, most of the proposed blockchain applications in construction lack a holistic approach to encompass the whole life cycle of a built asset. Although these use cases validate the potential of blockchain technology, they do not address the broader requirement of integrating data across all phases of a built asset's life cycle. Effective information management must cover the full spectrum of activities from design and construction to operation and maintenance. Focusing on isolated phases or processes limits the potential benefits of blockchain technology, such as improved data integrity, security, and transparency across the entire project life cycle.

Another critical limitation is the lack of empirical evidence on the needs of the industry stakeholders and current practices. Many studies are theoretical or based on limited practical implementations. Majority of the studies propose replacing existing CDEs with new blockchain-based solutions. This approach assumes stakeholders would abandon their current tools and transition to a single blockchain-based CDE. From the previously mentioned studies, only Ciotta et al. (2021) proposed the integration of various CDEs in the construction phase, however, they focused only on the integration of CDEs from appointed and appointing parties. As devised by Jaskula et al. (2024), one of the most significant challenges in practice is the use of multiple CDEs simultaneously in all life cycle stages. Moreover replacing all of them with one CDE is not feasible due to their complexity and specific requirements of different project phases and stakeholders. This practical challenge necessitates a solution that can integrate data across multiple CDEs without requiring a complete overhaul of existing systems. Therefore, in this work, we investigate firstly the needs of the industry and secondly how blockchain could be implemented throughout all of the life cycle phases to address current challenges.

Research Methodology

This study uses a qualitative, participatory research methodology that is especially influenced by design science research (DSR) methodology (Peffers et al. 2007). DSR emphasizes exploration through design, highlighting its fundamental divergence from other research methods (Holmström et al. 2009). DSR aims to develop "a means to an end," meaning the development of an artefact to solve a practical problem (Holmström et al. 2009). Järvinen (2007) emphasized that DSR is initiated by researchers interested in developing technological principles for a specific problem "in close collaboration with the local people." A typical DSR has the following steps: problem identification, objective definition, design and development, final demonstration, and assessment (Holmström et al. 2009). This research decomposes the DSR approach into four main stages (Fig. 2). The first two stages include desk research and fieldwork that focus on problem identification and objective definition. This leads to the identification of requirements in Stage 3 to support the development of a framework demonstrated in Stage 4. The assessment of the proposed method is presented in the "Discussion" section.

Collecting background information about the system that will be provided and how it is employed in operation is the first step in the user requirements analysis process. The information sources include all the users and stakeholders influenced by the system or published sources such as research papers and industry reports (Mo et al. 2015). In Stage 1, we conducted a systematic literature review to identify the challenges surrounding the implementation of CDE tools [presented by Jaskula et al. (2024) and summarized in the section "Information Management Challenges"] and core functionalities that CDE solutions should have. A systematic literature review is "a form of secondary study that uses a well-defined methodology to identify, analyse and interpret all available evidence related to a specific research question in a way that is unbiased and (to a degree) repeatable" (Kitchenham and Charters 2007, p. 6).

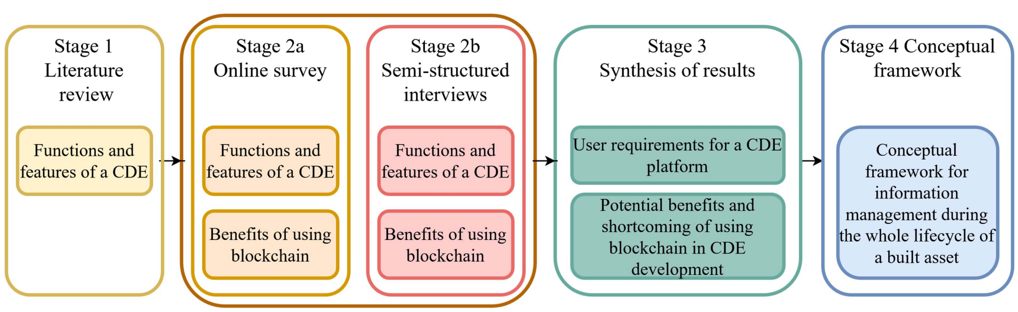

Fig. 2. Roadmap of the study.

This method was chosen because it provides a synthesis of the state of knowledge and identifies future research priorities (Page et al. 2021).

Defining user needs is largely influenced by user opinion which can be identified through different methods such as user surveys, focus groups, interviews or future workshops (Mo et al. 2015). To validate the functionalities specified in Stage 1 and discover the users' needs, we conducted semi-structured interviews (Stage 2). For brevity of scientific communication, the full results of Stage 1 will not be presented in detail here but will be embedded and directly tested in the structure of the fieldwork in Stage 2. In Stage 3, we present a synthesis of results providing an overview of blockchain features versus the shortcomings of current CDEs and user requirements that blockchain might address. Based on the outcomes of Stages 1 and 2, a conceptual framework for information management along the whole life cycle of built assets is proposed in Stage 4. The initial idea of the framework was developed by Jaskula et al. (2022). However, it was based entirely on the literature and did not include any empirical evidence. Therefore the framework presented in this study reflects current industry needs and is more practice-oriented than the previous one.

Findings and Results

Literature Review

To understand the state-of-the-art research surrounding CDEs, a systematic literature review was conducted following the the preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines for systematic reviews (Page et al. 2021). The detailed review process steps are presented in Appendix S1. Advanced search strings using Boolean operators were used on Scopus and Web of Science (WoS) databases because they cover business, economics, and engineering subjects. To find all relevant literature, the keywords "common data environment," "document management system," and "single source of truth" were selected because they are used interchangeably in the literature. The keyword "construction" was added to narrow down the results that were relevant to this study. The exact search strings are presented in Table 1.

The number of papers was limited to peer-reviewed journal papers to ensure high quality. Papers published before 2007 were excluded because it was before the ISO 19650 publication and definition of CDE terminology. Duplicates were removed, and 71 papers were selected for screening following the steps of PRISMA guidelines for systematic reviews (Page et al. 2021). Finally, 46 documents were selected based on their relevance to CDE. Selected papers were coded in NVivo software version 20 in search of CDE functionalities which are summarized in this section.

One of the most prominent and essential functionalities of a CDE is providing a single source of truth of all information along the built asset's life cycle (Daniotti et al. 2021). CDE should contain both BIM models and other information, including registers, schedules, contracts, reports, and model information and formats (e.g., PDFs or jpegs) stored as files (Charef 2022; Comiskey et al. 2017). Stakeholders should access all required information in a CDE without repeatedly switching between many applications (Taylor 2017).

Linking structured and unstructured data sources is a core requirement for developing a CDE (Patacas et al. 2020). Another fundamental requirement is data accessibility, which always needs to be updated throughout an asset's life cycle, including compliance with the newest technology (Charef 2022). The data should be accessible to all project participants, such as owners, inhabitants, designers, facility managers, or public authorities (Daniotti et al. 2021). Online CDEs would ensure that all participants acquire the right information at the right time and can exchange essential information in real-time (Jang et al. 2021; Zanni et al. 2020).

Interoperability is fundamental for efficient data exchange in the CDE; because the data are used for multiple disciplines, it must be available in a common, open format such as the industry foundation classes (IFC) (Charef 2022; Pérez-García et al. 2021). To enable unambiguous information sharing in a CDE process the files' naming must remain uniform and consistent using standardized file and layer naming conventions (Comiskey et al. 2017; Pérez-García et al. 2021). Having a unified terminology reduces miscommunication and misunderstanding among different parties (Sadrinooshabadi et al. 2021). Because corresponding data must remain useful during the whole built assets' life cycle, it is advisable to use nonproprietary formats starting with the early design (Turk et al. 2022). To ensure the continued use of data sources in future, the asset information model (AIM) data sources in O&M should also rely on open standards (Patacas et al. 2020).

CDEs should ensure that data can be traceable by providing historical records and revisions' history (Daniotti et al. 2021). Tamper-proof data flow should be ensured by maintaining the authenticity and integrity of information (Turk et al. 2022). Keeping track of the history and maintaining the traceability of information is especially important during a built asset's life cycle (Sadrinooshabadi et al. 2021). Access control is also important for ensuring the confidentiality, integrity, and availability of sensitive project data (Turk et al. 2022). Therefore, controlled access should be given to each team member according to their roles so that they only access their assigned areas (Comiskey et al. 2017; Turk et al. 2022). At the same time, it is undesirable to have one stakeholder with overall control of the model (Soman and Whyte 2020) because centralized administrators might manipulate the data or deny access to other users (Tao et al. 2021).

Other characteristics that CDEs should have are enabling three-dimensional (3D) model visualization (Nojedehi et al. 2022; Pérez-García et al. 2021), compliance checking with employers' and stakeholders' requirements (Demirdöğen et al. 2021; Sadrinooshabadi et al. 2021), providing engines for filtering and searching information (Daniotti et al. 2021; Roman et al. 2022), automating information checking (Sadrinooshabadi et al. 2021), and enabling feedback (Adamu et al. 2015; Comiskey et al. 2017), while preserving data quality and a high level of security, and maintaining a good organization and information structure (Pérez-García et al. 2021; Sadrinooshabadi et al. 2021).

Interviews Results

In Stage 2b, for the semistructured interviews, only experts in BIM adoption were sought because they have the best knowledge about

Table 1. Search strings

Database	Search string
Scopus	TITLE-ABS-KEY("Common Data Environment") OR ((TITLE-ABS-KEY("document management system") OR TITLE-ABS-KEY("single source of truth") AND TITLE-ABS-KEY(construction))
Web of Science (WoS)	TS=("common data environment") OR ((TS=("document management system") OR TS=("single source of truth")) AND TS=(construction))

Table 2. Semistructured interview participants' data

Interviewee	Position	Company profile	Years of experience	Country	BIM expertise	Blockchain expertise	Design and construction	O&M
1	Consultant	Standards, regulations, BIM implementation	20+	UK	Expert	Basic understanding	Y	Y
2	BIM manager/researcher	Project management, research	15+	UK	Expert	Expert	Y	N
3	BIM manager	Project management, architectural practice	5+	UK	Expert	Good understanding	Y	N
4	Consultant	MEP, HVAC planning	15+	Sweden	Very good	Good understanding	Y	Y
5	Blockchain developer, researcher	Blockchain applications development	<5	UK	Not applicable	Expert	N/A	N/A
6	Consultant/researcher	Implementation of IT in construction	30+	Denmark	Very good	Good understanding	Y	Y
7	Consultant	Smart buildings, sustainable construction, General Contractor	30+	Sweden	Very good	Basic understanding	Y	N
8	BIM manager	Project management, General Contractor	20+	Ireland	Expert	Good understanding	Y	N
9	Construction manager	Digital management, design management	10+	Ireland	Expert	No experience	Y	N
10	Consultant/researcher	Implementation of IT in construction	20+	Sweden, Denmark	Very good	Very good understanding	Y	N
11	BIM manager	Project management, architectural practice	5+	UK	Expert	No experience	Y	N
12	Consultant/researcher	Asset management from the owner side for infrastructure projects	10+	Estonia	Very good	Basic understanding	N	Y
13	Facility manager	Facility management of public assets	5+	Ireland	Expert	No experience	N	Y
14	Department manager	Digital construction in project management, General contractor	15+	Sweden	Expert	Basic understanding	Y	N
15	Development director	Facility management	20+	UK	Expert	Basic understanding	N	Y
	Total						11	6

Note: MEP = Mechanical, Electrical, and Plumbing; Y = yes; and N = no.

the practical implementation of CDE tools in practice. BIM experts were defined as professionals applying BIM tools and BIM methodology including methods described in the ISO 19650 standard on a daily basis in construction projects. Such target interviewees were project managers, BIM managers, and general contractors as well as facility managers, as insights about information management in all phases of assets' life cycles were searched for. Individuals from the researchers' professional network were identified and asked to participate in the interview.

The interviewees have been chosen based on their tendency to participate, knowledge, background in AECO, and experience with BIM-based project management. First, the interviewees were asked to introduce themselves and talk about their experience with information management and the challenges they encountered when using CDE tools. Afterward, they were asked to describe their expectations about the CDE tools and elaborate on the possible improvements compared with the tools that they are currently using. In the end, they were asked to give their opinion on implementing blockchain technology in CDE-based information management. The list of questions is included in Appendix S3.

As a main analysis method for interview data, we utilized thematic analysis via coding (Braun and Clarke 2006). Through coding, a researcher can identify themes or patterns in the qualitative data that can be further investigated (Saunders et al. 2019). The publications and interview transcripts were imported to NVivo 2020, and code-related text excerpts related to challenges of CDE adoption and use were highlighted to recognize their frequency throughout the transcripts. The first coding cycle, called initial coding (Saldaña 2009), was used to identify preliminary codes. It was followed by focused coding (second cycle) to identify the most frequent or significant initial codes and led to the development of prominent themes in the data set (Saldaña 2009).

In total, 15 professionals were interviewed from different companies, positions, and years of experience, as reported in Table 2. The interviews took place between November 2021 and April 2022. Each interview took between 40 and 80 min, and the recordings were transcribed and verified. Most interviewees were already familiar with blockchain, but for those with little or no relevant knowledge, the researcher gave a short presentation regarding blockchain and its potential implementation during the asset's life cycle.

User Requirements

The pivot discussion of the interviews focused on the question of what CDE's most important functionalities are. Six main themes emerged after analyzing the results (Table 3).

One Source of Truth

A CDE's primary purpose and function is to store all information in one place. A CDE "probably isn't a single tool or product that could be used like everyone can jump onto, but it's more likely that we could all agree on something independent that we can connect to, and we can maintain that with interfaces" (Interviewee 15).

Table 3. Functionalities of a CDE based on interview results

Functionality	Total	Design and construction	O&M
Single source of truth	6	4	3
Tracking historical records	6	4	4
Linking files	6	4	3
Data analytics	6	3	3
Documented participation	4	2	2
Managing identity	3	2	2
Task management	2	1	2

Interviewee 8 sees CDE as "a number of ecosystems to interact with each other" and believes that "there's a massive value [. . .] to track all of the data, how it goes between the different applications and platforms." However, developing an "enormous tool to do everything" is a considerable risk. It might be better to have "lots of little tools that speak to each other." Interviewee 15 believes that "the secret for the common data environment is connecting it to tools that are genuinely being used every day." Professionals already have the tools they are using, and they would prefer to continue doing so.

Tracking Historical Records

Storing the record of all previous data versions and files is one of the most desired CDE functionalities. Interviewee 6 expressed that it would be advantageous "if you could track that and you could see [. . .] why you have chosen this solution, the reason behind it." Understanding why and how something wrong happened in the project is important to avoid similar mistakes in the future. Moreover, reusing knowledge on successful solutions from previous projects should be possible through a CDE as it "has been traditionally hard to drive the development and get an experience exchange between different parts of own company." It isn't easy to spread this knowledge to another team, even in the same company (Interviewee 7). Interviewee 4 expressed a wish that his company "want to be a part of that (process), not just deliver deliverables at a specific date, but also want to see if the building works, the climate, the indoor climate works and all the other stuff that the energy performance is at the level that we predicted or planned."

Linking Files

Project data are usually scattered between different tools and platforms; keeping the relationships between all the data stored and exchanged in different platforms is impossible. Therefore understanding the reasons for some decisions or the consequences for other disciplines is challenging. Interviewee 6 described, "you have to make some solution to fulfil some of the requirements that have some impact on the previous requirements and so on and [. . .] if you make some changes over here, what impact does it have?" It is important to receive all the possible effects of an object's change on all the other elements associated with the initial change.

Interviewee 8 gave an example of a steelworker who might be concerned about the roof but wants to see everything around the roof even if it is not a steel issue, but, e.g., an issue directly beside the steel. The more granular each package can be broken down, the better. "What needs to happen is that the drawing connects to the model, connects to the claim, connects to the valuation, connects to the supplier, connects to that piece of information that's gone to the factory to get manufactured, to the truck, to landing, to be in place, to write to handover" (Interviewee 8). Interviewee 14 explained that understanding the other stakeholders' work and decisions is important for effective collaboration. That could be achieved by seeing others' work, its relation to own work, and understanding another software's results and content, which would significantly improve the transparency of the collaboration process.

Data Analytics

According to Interviewee 14, a CDE should "give some information that you can rely on and that it's easy to find and also that it's maybe a little bit more intelligent so that you get some suggestion. It doesn't need to be intelligent to start with it; it's enough if I could interpret exactly that data from different sources because that is one of our big problems." Interviewee 12 suggested that the use of artificial intelligence to classify and analyze the increasing amount of information should be investigated: "There is just so much information, and I cannot put the hours to work the information. So just the simple classification or just simple detection would help to make better or good enough decisions, more accurate."

Interviewee 14 expressed the importance of understanding the data from different sources and enabling lessons learned from other projects. Having a complete picture of all combined data would lead to better decision-making. Moreover, artificial intelligence (AI) could analyze all the information from the operational stage to predict maintenance. "If you can bring information into a digital twin along with BMS information, power consumption and so on, it should be able to predict when the piece of equipment is going to fail before it does and should be able to warn you in advance there's something going wrong. The bigger goal is that you can reduce the number of maintenance visits that you have" (Interviewee 13).

Documented Participation

A CDE should provide an accountable record of events happening during the whole asset's life cycle, including documenting each stakeholder's participation in the project. In case of any disputes, it is essential to allocate the responsibility for each occurring problem. Through CDE, it should be possible to provide proof of each event, in case legal or other liability arise. According to Interviewee 2, CDE "should have measured participation in the project; otherwise, it becomes a very chaotic counterproductive process." Interviewee 11 highlighted that accurate distribution of information is especially important from a designer's perspective: "so the right people get the right information when they need it." It is critical "that information is going through the right set of eyes and getting signed off by the right people. And obviously, that process is recorded and documented, [. . .] so if someone's received something and they haven't acted on it, that's on them" (Interviewee 11).

Other Functionalities

Facility managers wish for a CDE to handle task management, simplify, and speed up their daily tasks (otherwise planned by themselves). Graphical data stored in CDEs should enable easier identification of task location and provide more detailed information about task requirements. This way, facility managers would know exactly what to do and avoid waste of time and resources.

Some interviewees expressed the idea of extending a CDE to more than just a platform for project information exchange. CDE data about each stakeholder's performance could be used to build their career reputations. Interviewee 4 described it as "something more than just a common data environment, something more like a sort of platform where you can create a profile [.] the more you use the platform, the more experience points you get and people can see that and you can build trust."

CDE Features

Apart from specific CDE functionalities, interview participants expressed their wishes about CDE characteristics and data treatment. The most often mentioned CDE features are presented in Table 4. A key priority for developing a CDE is the tool's ease of use. A new CDE should be easy to implement and not require too much effort to learn the new tools and methods. Ideally, the users would like to keep utilizing their old tools and methods. Equally important is the transparency of the information management process. Providing controlled access to data depending on each stakeholder's role was also mentioned as a significant CDE feature. The need for automation of repetitive tasks in all life cycle phases was noted as another crucial CDE feature.

On top of that, the CDE should enable long-time storing of information to match a built asset's long life cycle. The ability to

Table 4. Features of a CDE according to interview participants

Feature	Total
Ease of use	7
Transparency	7
Controlled access	6
Automation	6
Long lifespan of data	6
Legal binding	5
Open source platform	4
Scalability	4
Security	4
Reasonable cost	4

legally prove the information and events happening during a building's life cycle is also demanded, especially in the case of disputes. Other features mentioned by the interviewees were creating an open-source solution instead of being required to use commercial solutions; providing enough scalability because the amount of information is constantly growing; ensuring high-security levels; remaining reasonable with the tool's costs so that they correspond to its benefits; and lastly, staying flexible for potentially needed human interventions and individual adjustments.

Blockchain for CDE

In the last part, the interviewees were asked about using blockchain for information management in construction projects. The most often mentioned benefits of using blockchain are presented in Fig. 3. Most interviewees were rather enthusiastic about blockchain's relevant potential improvement in information management. The most often mentioned advantage of using blockchain is improved transactional accountability and trust.

Interviewee 13 stated that currently, on the operation side, it is challenging to identify who is accountable for making a mistake, whereas "if you had the blockchain data and all the information was there, say who did it and when and what stage and what decision they made and so on. Then that will be a lot easier to say it is your problem to fix, not ours." As Interviewee 1 described it, "what blockchain is meant to be good for is creating trust in an environment where there isn't anything else." Some of the interviewees were convinced that placing data on blockchain will improve the overall resiliency of the information as "you know that in 100 years time, it will be there [and] data resilience is very important above and beyond cyber security" (Interviewee 2). By using blockchain, "you create your system that resists system failure and resists militia, malicious attacks [. . .] a system that is resilient so you can rely on that data going forward" (Interviewee 2). Improved data ownership protection, traceability, and providing legal proof of events were noted as very useful for AECO as well.

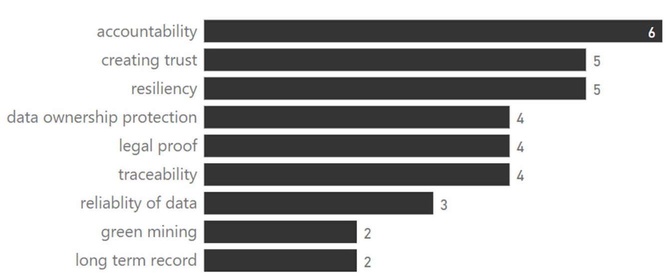

Fig. 3. Possible benefits of using blockchain for construction information management by interviewees' answers.

Synthesis of Results

Based on the Stage 1 and 2 findings, we mapped the identified CDE requirements, functionalities, and features described by stakeholders with the challenges defined in the previous study (Jaskula et al. 2024). We aligned them with blockchain features identified as helpful in tackling those challenges (plus sign) and those that might be disadvantageous (minus sign). The outcomes of this synthesis are presented in Table 5.

Because interviewees were professionals from the construction industry, their requirements were mainly related to what they expect from a CDE and did not focus on the technological requirements toward blockchain-based solutions. The top requirement supported by both empirical data and literature is providing a single source of truth for all project data. Because multiple CDEs are currently used simultaneously and replacing them with one tool is not feasible, a new method to integrate them is highly anticipated. Providing an immutable record of transactions based on the blockchain might help overcome some of the identified challenges, such as using multiple information sources, lack of data traceability, lack of trust in data accuracy, and data ownership tracking. Blockchain can interact with other software through smart contracts, application programming interfaces (APIs), or decentralized applications, thus integrating all data records from multiple sources in one place and keeping them always updated and accessible for all stakeholders. Therefore, a vendor-neutral and scalable blockchain solution is preferable.

At the same time, blockchain should provide a long-term, resilient transactional record, with which all information can be tracked back in time, even after many years of an asset's life cycle have passed. For this reason, well-established blockchains such as Ethereum would be most suitable. Because all transactional metadata (including the author and time stamp) are also immutable, the problem of data ownership tracking could be solved. Improving trust in digital information might contribute to overcoming the challenge of AECO's low digitalization. Stakeholders should be encouraged to share information through blockchain without the fear of losing their intellectual property or not being able to prove their rights in case of a dispute.

However, some of the identified problems cannot be solved only by implementing a blockchain-enabled CDE. The interoperability between different formats remains one of the most significant issues that will not be improved by storing data on a blockchain. The variety of data formats that are not interoperable will remain whether they will be saved on the blockchain or a cloud. However, blockchain enables saving data in all different formats, so the exchange of exported and imported data could be well-documented at least. The lack of skills might also be problematic for establishing a blockchain-enabled CDE, because blockchain is a novel technology requiring expert knowledge for its implementation. Coding smart contracts is a complex task and their correctness is crucial because they are not easily adaptable. However, using blockchain as the background layer and providing user-friendly interfaces to access the data might solve the problem because the end-user will not need any blockchain expertise to use the software.

Conceptual Framework

Whole Life Cycle Information Management

Based on the identified user requirements, we propose a conceptual framework for information management based on blockchain during a built asset's whole life cycle (Fig. 4). The framework uses a sequence diagram in the Unified Modeling Language (UML)

Table 5. Data synthesis based on outcomes of Stages 1, 2, and 3

User requirements	Challenges	Blockchain features
Single source of truth	Using multiple sources	+ Connecting sources through APIs and recording transactions from all different tools on the blockchain
Ease of use	Lack of skills and knowledge about the standards Low digitalization	+ Requires technical skills to implement + Could work as a background layer not noticeable by the users
Automation, task management	Manual processes	+ Automation by using smart contracts
Documented participation, historical records tracking, transparency, long-term storage	Handover issues, lack of traceability	+ Providing transparency and accountability + A long-term and immutable record of events
Historical records tracking, Documented participation and responsibility, transparency, legal binding	Lack of traceability of data	+ Immutability of blockchain record + Improving trust in digital data exchange + High security + Providing long-term and immutable information record
Link files, Data analytics	Not understanding data, missing information	+ Possibility of integrating AI solutions
Interoperability, open-source platform, reasonable cost	Monopoly of software vendors	+ A neutral solution can be open source
Interoperability	Lack of interoperability	+ All data files can be stored − Does not improve the compatibility of different formats
High security, immutability	Low security	+ High security
Access level control, immutability	Centralization of data	+ Decentralization
Scalability	Computational burden	− Requires a high amount of computational power to run
Transparency, documented participation	Data ownership tracking	+ Tracking of metadata + Immutability

because it is one of the best methods to show sequences of interactions between multiple objects over time (IBM Corporation 2021). The framework covers the fundamental interactions between chosen stakeholders and tools during the whole life cycle of a built asset, including the preparation, design, construction, handover, O&M, and termination phases. Apart from stakeholders, other objects included in the framework include multiple CDEs and facility management tools identified in this study. The interactions are illustrated chronologically from the framework's top to bottom.

One of the main identified problems is using multiple sources of information during each phase and across the entire life cycle. The top CDE requirement is to provide a reliable single source of information. In the framework, we propose to record all transactions from different sources across the life cycle on a blockchain. Based on the study's results, it is assumed that using multiple platforms and tools during the project life cycle is inevitable. Proposing a new CDE that could replace all the information management software currently used in AECO is extremely complex and most likely impossible. Instead, an effort should be put into linking all presently used tools and tracking the transactions between them. A new approach to CDE development should focus on integrating existing fragmented software systems and tools rather than proposing another CDE tool that would be used in parallel with the others.

Blockchain could secure data integrity between the tools and provide immutability, security, transparency, and trust in the collaboration process, highlighted as valuable input by stakeholders participating in this study. Integrating the data from different tools in one place from the beginning of the project would enable the easier gathering of handover information at the close-out stage, which a series of smart contracts could also automate. According to the framework, all project stakeholders would have access to the required information. Stakeholders can continue using the programs they are currently utilizing, and each tool would be connected to the blockchain to record the transactions between them. The record is available through a dashboard, enabling access and tracking of the information at any moment. The dashboard should also provide data synthesis and analysis, possibly by integrating AI, as the users require.

As identified in the interviews, multiple CDEs are used simultaneously during the design stage. For example, the client might set up a CDE, such as Aconex or Viewpoint, for managing documents and submittals. At the same time, the general contractor or designers might use Autodesk BIM 360 as a CDE for BIM coordination. In the framework, we track the transactions from all of the utilized CDE tools (e.g., exchanging BIM files, drawings, reports, and emails, design revisions, or approvals and rejections of submittals by each party) by saving their signatures on the blockchain. To achieve integration, we suggest the use of smart contracts that communicate with the APIs of each tool. These smart contracts could record the metadata of all transactions on the blockchain, similar to prototypes developed by Das et al. (2021b) and Tao et al. (2021). This means that all transactions will be automatically and instantly recorded on the blockchain without requiring active user involvement.

However, to avoid data redundancy, all large files (e.g., every version of a BIM model) cannot be saved on the blockchain; instead, the files' hashed signatures should be stored to enable later validation and detect any data manipulation. We propose using an IPFS storage to save large files because most of the blockchain networks cannot do it. Storing files on a distributed storage instead of a centralized cloud-based repository adds another layer of security and prevents data tampering by the central authority. To solve privacy issues of content stored on the IPFS, the files should be encrypted with the private keys of the authorized users so that only they could decrypt the information.

During construction, BIM platforms and document management systems may remain the same as during the design phase

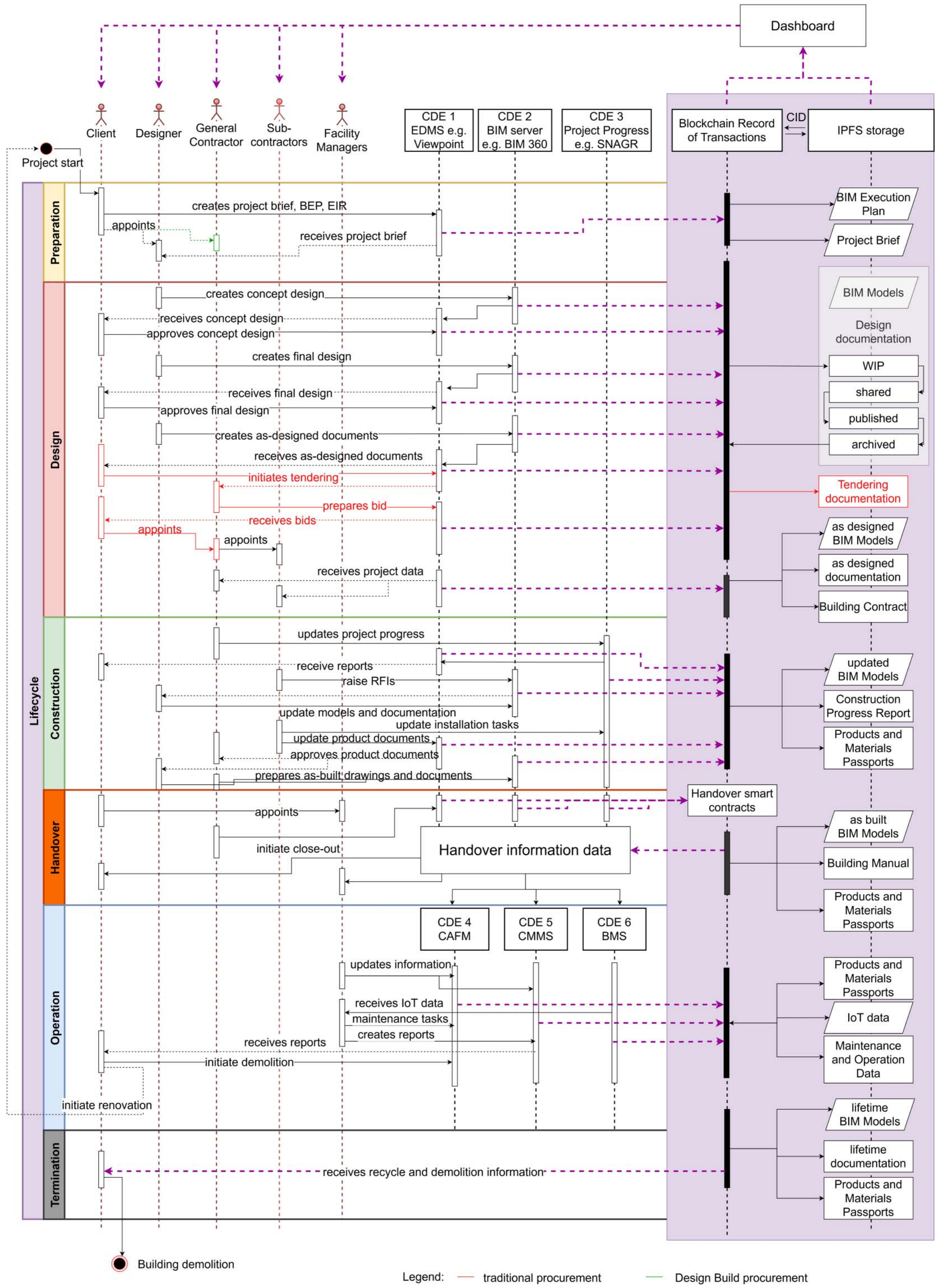

Fig. 4. Conceptual framework for blockchain-based information management.

or may be changed to a different set of tools as another company might overtake the project. It might also happen that additional tools, e.g., for tracking project progress, will be used. In all cases, the transactional record on the blockchain should be continued for all used platforms and tools.

Additionally, a CDE should start recording information about the installed products and materials in so-called material passports (Copeland and Bilec 2020), which should be established when a product is installed. In later project stages, each product's data should be constantly updated by relevant stakeholders, including their installation information, manuals, maintenance, and replacement during O&M. At the end of the construction phase, all the necessary data from previous phases should be handed over to the facility management system through a series of smart contracts, which will be filtering only the information needed for handover. At the same time, the rest will remain accessible in read-only files. The data should remain available throughout the built asset's whole life cycle. During the O&M phase, the CDEs used in the previous phases are replaced with a new set of tools such as CAFM systems, computerized maintenance management system (CMMS), or BMS tools. The information about asset operation and maintenance from those tools should be recorded on the blockchain so that at the asset's end of life, all data (including material and product passports) can be updated and used to estimate possible reuse or recycling of materials.

Use-Case Scenarios

To verify the proposed framework's applicability, we define three use cases, each corresponding to a different realistic scenario inspired by distinct challenges shared by the interviewees. These cases address different phases of the project life cycle: design, construction, and O&M.

Design Stage Scenario

In the first scenario (Fig. 5), stakeholders use two CDEs to exchange design information. As reported by all the interviewees, it is common to use one CDE such as BIM 360 for design coordination, which includes the exchange of 3D models and drawings and a second CDE, such as Aconex or Viewpoint to facilitate the process of submissions and approvals between stakeholders. Because design changes can occur daily and the approval process can take multiple days, subcontractors may use outdated architectural drawings for detailing. In this scenario, an architect uploads a new version of a ceiling drawing before the previous version gets approved by the client. The transaction will be immediately recorded on the blockchain, and a smart contract will notify the HVAC engineer immediately about the update. This will help the engineers use the newest plan version to detail the installations.

Detailed Walkthrough

The process includes the following steps:

1. Design update:
   - An architect creates a new version of a ceiling drawing to address a design change.
   - An updated drawing is uploaded to BIM 360, initiating a new transaction on the blockchain.
2. Blockchain recording:
   - The blockchain records the transaction instantly, ensuring that the update is immutable and time-stamped.
   - A smart contract triggers a notification to relevant stakeholders, such as the HVAC engineer.
3. Notification and coordination:
   - The HVAC engineer receives an immediate alert about the updated ceiling drawing.
   - The engineer accesses the latest drawing from BIM 360, ensuring they work with the most current information.
4. Approval process:
   - Meanwhile, the approval process for the new drawing version continues on CDE (such as Aconex or Viewpoint).

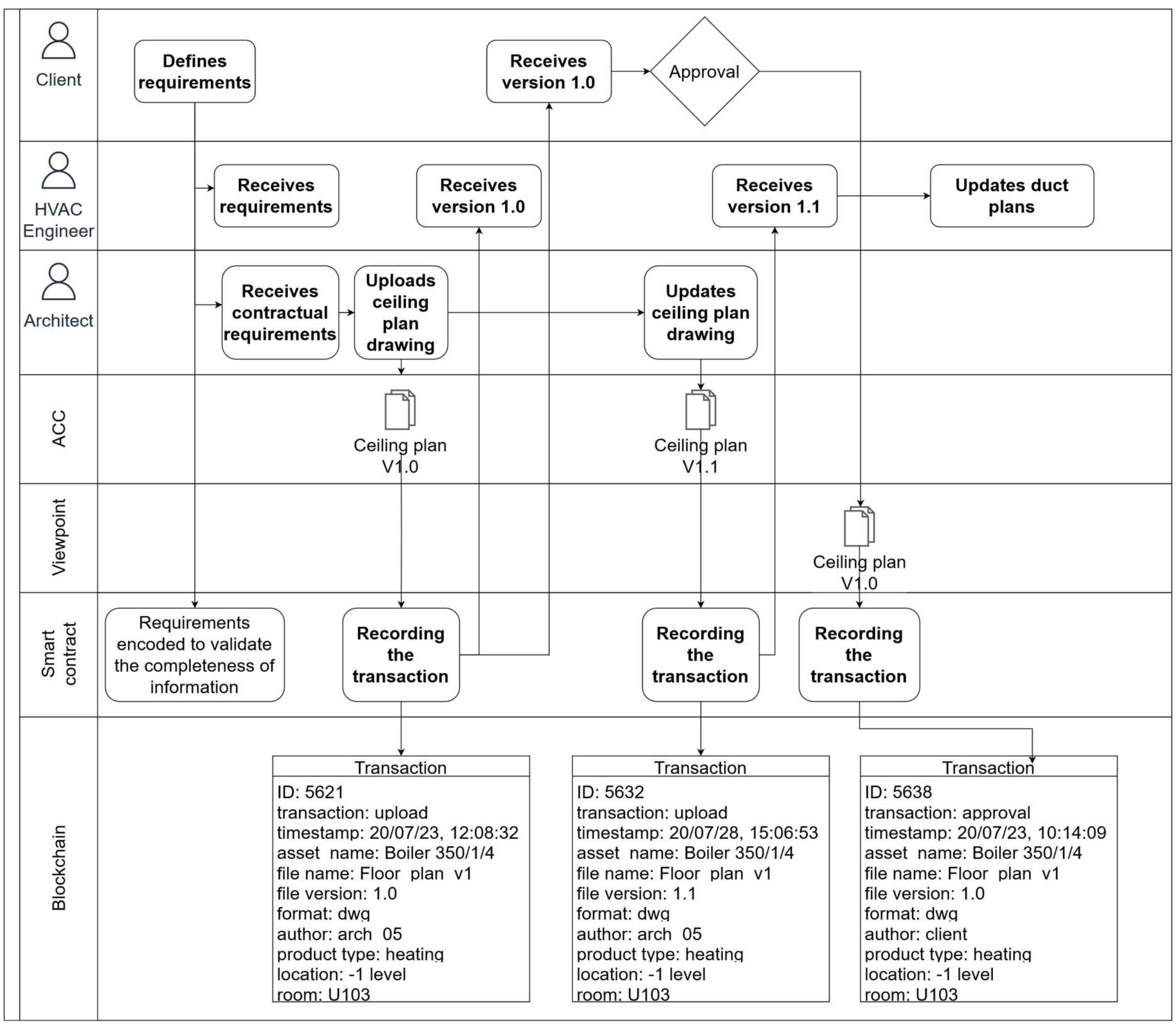

Fig. 5. Design phase scenario.

- Even though the official approval might take several days, all stakeholders are already working with the latest design information due to the blockchain notification.

This real-time update mechanism mitigates the risk of subcontractors using outdated drawings, thus reducing errors and rework. The blockchain ensures that all changes are transparently tracked and verifiable, enhancing accountability and coordination among the project team.

Potential challenges in this scenario include interoperability issues and scalability of the blockchain. Different CDEs may have varying levels of compatibility and interoperability, making seamless integration difficult. Implementing standardized data formats and APIs can help facilitate smoother interactions between different CDEs. Blockchain can act as a unified ledger that links disparate systems through smart contracts and standardized data entries. As the number of transactions increases, the blockchain network might face scalability issues, potentially slowing down the system. Utilizing scalable blockchain solutions such as Layer 2 protocols or sharding can help manage a high volume of transactions efficiently.

Construction Stage Scenario

The second use case displayed in Fig. 6 follows the order and installation of an air-handling unit (AHU). In the moment of AHU approval and order, a product passport is established. The product passport is automatically updated once the AHU is installed and recorded in the SnagR platform. When the subcontractor uploads required documentation to the CDE, such as a warranty or a manual, the passport is updated again. The passport is updated whenever new information is uploaded to any of the CDEs used during the project life cycle, providing a complete product history.

Detailed Walkthrough

The detailed walkthrough for this case is as follows:

1. Approval and order:
   - Upon approval of the AHU, a product passport is created on the blockchain.
   - This passport contains initial details such as manufacturer information, specifications, and order confirmation.
2. Installation:
   - When the AHU is installed, the event is recorded in the SnagR platform by the subcontractor.
   - The blockchain updates the product passport with installation details, including the installation date, location, and responsible subcontractor.
3. Document upload:
   - The subcontractor uploads required documentation to the CDE, such as warranty information, user manuals, and maintenance schedules.
   - Each document upload is linked to the product passport via the blockchain, ensuring all relevant information is easily accessible.
4. Ongoing updates:
   - Throughout the project life cycle, any new information related to the AHU, such as maintenance records, inspections, and part replacements, is uploaded to the CDE.
   - The blockchain continuously updates the product passport, providing a comprehensive history of the AHU.

The blockchain-based product passport offers a complete and transparent history of the AHU, from approval to end of life. This ensures that all stakeholders have access to accurate and up-to-date information, facilitating better decision-making and maintenance management.

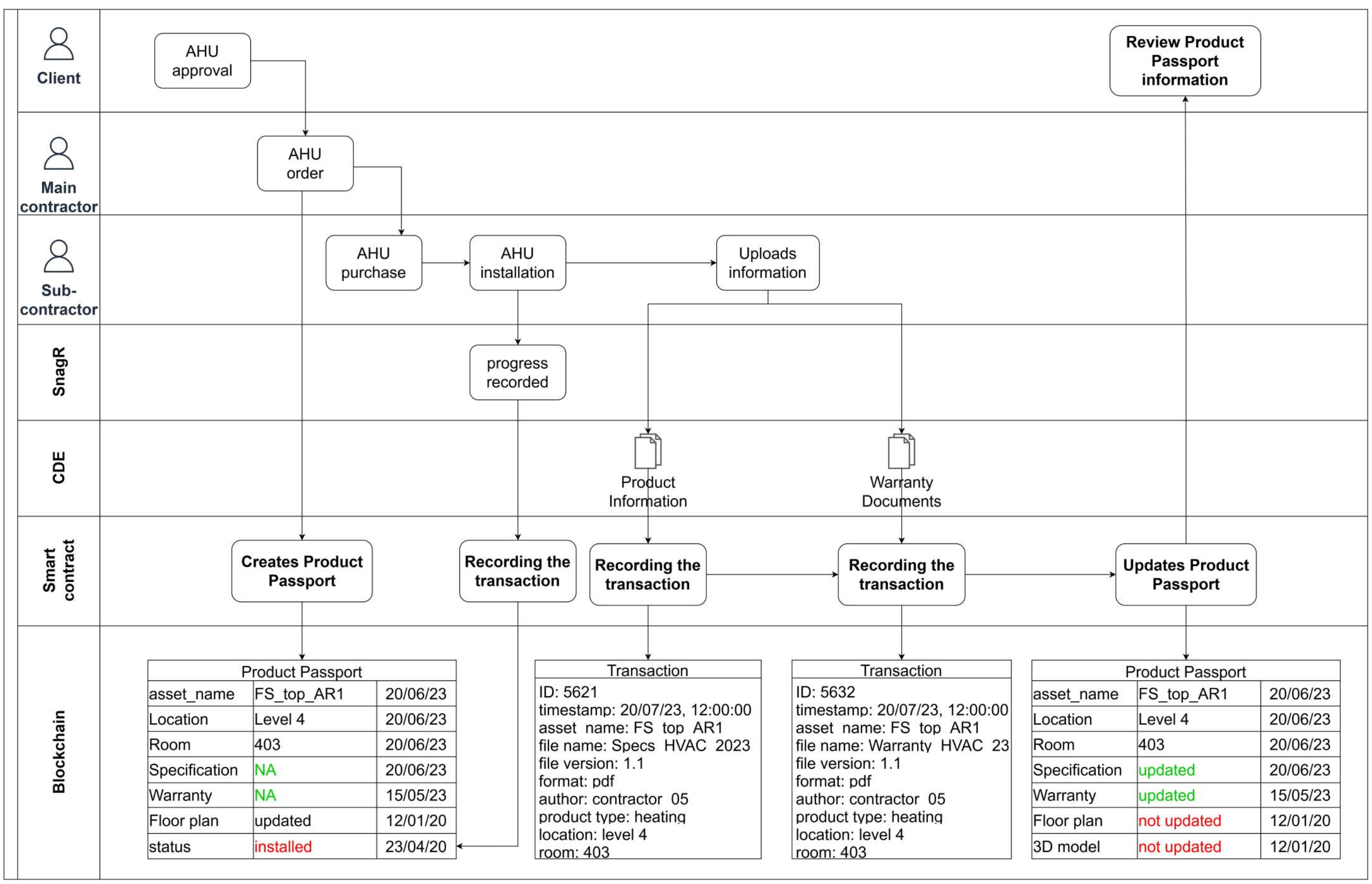

Fig. 6. Construction phase scenario.

Challenges in this scenario include ensuring data accuracy and verification, integration with existing systems, and cost considerations. Ensuring that all data entered into the blockchain are accurate and verified can be challenging. Implementing rigorous data verification processes before data are recorded on the blockchain can help maintain data integrity, including multiple stakeholder approvals or automated validation checks. Integrating blockchain with existing CDEs and platforms may require significant technical adjustments. Developing middleware solutions or APIs that facilitate seamless integration can help overcome this challenge, and collaborating with CDE providers to ensure compatibility can also be beneficial. However, the initial setup and ongoing maintenance of a blockchain-based system can be costly. Conducting a cost–benefit analysis to demonstrate long-term savings and efficiencies can justify the investment, and leveraging consortium blockchains where costs are shared among participants can reduce the financial burden.

O&M Stage Scenario

In the third scenario, a use case from the O&M phase is presented (Fig. 7). Over the years of the building's life cycle, the FM team managing and operating the asset may change even multiple times, as Interviewees 13 and 15 reported. In that case, the CAFM system used for data storage is likely to be changed as well, meaning that data must be manually transferred from the old system to the new one. In our scenario, blockchain records the transactions from the old and the new CAFM systems. This way, the history of each product is consistent and complete and can be traced using the product passport enabled by blockchain.

Detailed Walkthrough

The detailed walkthrough for this case is as follows:

1. Facility management (FM) team transition:
   - When a new FM team takes over, they may choose to use a different CAFM system. Blockchain records the transactions

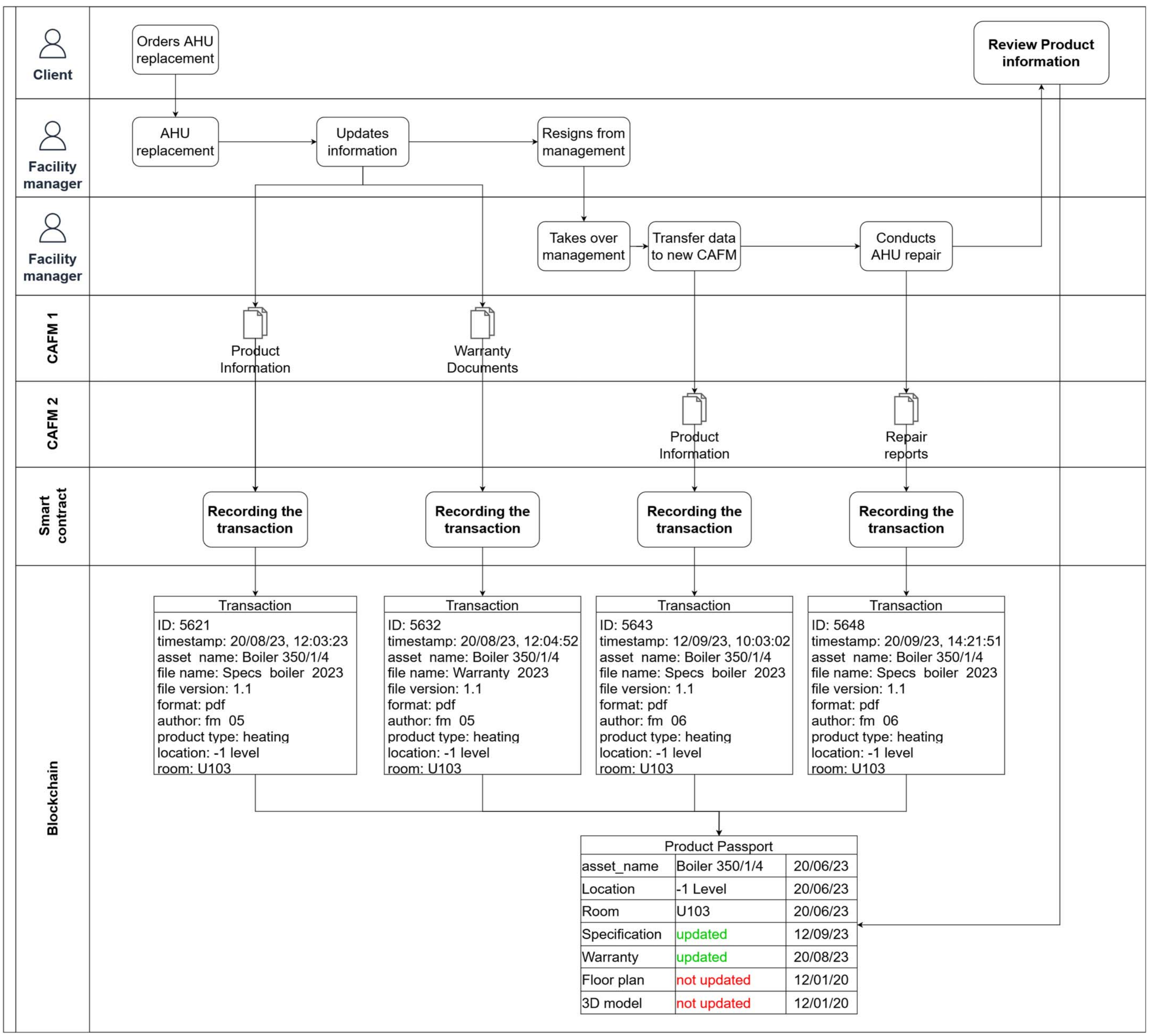

Fig. 7. Operation and maintenance phase scenario.

and data entries from both the old and the new CAFM systems.

2. Seamless data integration:
   - As the new team inputs data into the new CAFM system, the blockchain ensures that all historical data are preserved and accessible. The product passport for each asset is updated accordingly.
3. Consistent history tracking:
   - The blockchain provides a consistent and complete history of each product, accessible through the product passport. This enables the new FM team to seamlessly continue maintenance and management activities without losing critical historical data.

Potential challenges in this scenario include data migration complexity, resistance to change, and security concerns. Migrating data between different CAFM systems can be complex and error-prone. Utilizing blockchain as an intermediary simplifies the process by providing a consistent format for data storage, and automated migration tools and validation processes can further reduce the risk of errors. FM teams may resist transitioning to new systems and processes. Demonstrating the benefits of the blockchain framework, such as improved data integrity and reduced administrative burden, and offering training and support during the transition can ease the process. Ensuring the security of sensitive FM data on the blockchain is crucial. Implementing robust encryption and access control mechanisms can protect data privacy and security, and regular security audits and compliance with industry standards can further enhance trust in the system.

Discussion

Knowledge Contribution

This study defined the user requirements of a CDE and the potential use of blockchain technology for this purpose. The outcomes of the previous study (Jaskula et al. 2022) showed that currently used CDE solutions are still not entirely in line with ISO 19650. The literature review and the interview responses highlighted the diversity of CDEs used and the use of unstructured communication channels outside of the CDE workflow. This leads to a lack of trust in data accuracy and causes numerous problems with data traceability, integrity, and accountability because the different CDEs usually do not communicate with each other, and it is nearly impossible to track the transactions between them. The handover of project data from construction to the O&M phase was described as the weakest point of the whole information management workflow during the life cycle of a built asset.

RQ1 focused on defining the stakeholder requirements for a CDE based on the interviews with professionals using CDE in daily work. One of the main CDE requirements is to improve the traceability of information flow and provide a new solution for a single source of truth. Stakeholders wish to have one reliable source of information that would enable easy tracking of information about past events during each project phase. Recorded data should provide a legal liability to solve future disputes about the distribution of responsibility. The CDE should also enable an easier understanding of the decisions taken in the past by providing a comprehensive overview of project progress at any point.

RQ2 focused on proving how blockchain technology can facilitate the information management workflow across an asset's entire life cycle. According to the results of this study, many problems encountered currently in the information management workflow, such as lack of transparency and traceability of information, could be tackled by applying blockchain-based CDE.

In line with the collected requirements, a conceptual framework for information management along the built asset's life cycle was developed. The framework integrates the data from different tools and platforms used along the entire life cycle of a built asset in one place. A complete and reliable record of the history of the project provided by blockchain would improve the handover process and alleviate the problem of the broken information chain occurring currently at the close-out stage. An important part of the framework is enabling users to access and validate required information at any time through a user-friendly dashboard. The framework was validated through three illustrative use-case scenarios showcasing how it would improve the traceability of information. Integrating information from different platforms would enable the creation of trustworthy and complete product and material passports, which are the key tools to facilitate circular economy in the construction sector.

This research extends current knowledge by analyzing the practical and theoretical implications of decentralized information management in construction. Unlike previous studies, which often focused on isolated technical implementations (Ciotta et al. 2021; Das et al. 2021b; Hijazi et al. 2023; Tao et al. 2021), this work has synthesized findings from literature and industry interviews to develop a holistic framework that integrates blockchain, IPFS, and product and material passports across the entire asset life cycle.

Existing studies discussed decentralization primarily from a technological perspective, but this research advances knowledge by identifying the sociotechnical barriers and industry-adoption challenges. It contributes to the understanding of how decentralized models can improve trust, interoperability, and data sovereignty in construction, particularly in multistakeholder environments. This study enhances knowledge by demonstrating how IPFS can complement blockchain to improve data integrity, long-term accessibility, and security in CDEs, while addressing challenges like large file storage and regulatory compliance. Furthermore, this study advances knowledge by showing how material and product passports can serve not just as repositories of material data but as dynamic records that evolve with project phases, enhancing traceability and sustainability practices. By framing these technologies within a broader information management strategy, this research moves beyond engineering applications to offer a theoretical foundation for future studies on decentralized digital ecosystems in construction.

Compared with other studies investigating the use of blockchain for CDE development and information management, this work has proposed to integrate the existing CDE platforms used in the industry, instead of proposing another CDE tool to replace them. This approach was selected to enable data integration along the whole life cycle of a built asset and provide a single source of truth for all asset information. As identified in this and previous studies (Jaskula et al. 2024), developing a single tool for information management during the whole life cycle is not possible because in each of the phases, the tools have completely different requirements and functions. It might be feasible to develop a CDE tool for the design and construction phases, and many software vendors such as Aconex or Autodesk have succeeded in doing that. However, the practice shows that even though the solutions are there, they are rarely implemented for the entire project information. This is partially caused by the centralized character of those solutions, hindering all stakeholders from entrusting all their sensitive information in the hands of one party. Therefore, providing a solution which is more decentralized and integrates the databases used along the project life cycle could bring significant value to the industry and improve trust between construction stakeholders.

The integration of multiple CDEs was one of the top user requirements identified in this study. Some software providers, such as Newforma or BIMlauncher, have already attempted to address this demand in the industry. They both provide a tool that connects multiple CDEs in one place (BIMlauncher 2023; Newforma 2024). However, these solutions do not leverage blockchain technology, and therefore do not offer the same level of immutability, decentralization, and security that blockchain can provide.

Limitations and Future Directions

This study's focus was to investigate whether blockchain might be used to overcome the challenges of current information management in construction and address the stakeholders' requirements for a CDE solution. As a result, a conceptual framework including a blockchain-based transactional record was proposed. The next step of software development after defining the user requirements would be to define detailed functional and nonfunctional requirements to support the specification of the tool's architecture, which was outside of the scope of this study. A technological solution to collect data from multiple software used along the asset's life cycle still needs investigation.

Integrating the proposed blockchain-based CDE with existing data management systems and tools, such as BIM 360, Aconex, and Viewpoint, is crucial for its successful adoption. Interoperability can be achieved through several strategies. Firstly, developing APIs is essential. APIs could facilitate seamless data exchange between the blockchain-based CDE and traditional systems, ensuring real-time synchronization of documents, updates, and transactions. Standardizing data formats and protocols via APIs ensures compatibility across platforms.

Secondly, leveraging middleware solutions can bridge the gap between blockchain technology and existing tools. Middleware acts as an intermediary layer, translating and transferring data between the blockchain and conventional CDEs without significant changes to existing systems. Industrywide standards for data exchange, developed by organizations like ISO and BuildingSMART, should be aligned with the blockchain-based CDE to facilitate smoother integration and wider acceptance. Conducting pilot projects can also identify and resolve potential issues before full-scale implementation, refining the integration process. By focusing on API development, middleware solutions, adherence to industry standards, and thorough testing, the proposed blockchain-based CDE can effectively integrate with existing data management systems, enhancing data integrity, traceability, and transparency across the project life cycle.

Although blockchain offers enhanced security and traceability, it may not always be the best solution for a CDE. For example, large organizations with robust centralized CDEs already have systems that effectively ensure data integrity, making blockchain's added complexity unnecessary. Conversely, smaller firms might find blockchain too complex and expensive to implement due to the need for specialized expertise in managing smart contracts and distributed storage. In these cases, traditional centralized CDEs may be more practical and cost-effective. Blockchain can enhance CDEs in specific scenarios, but it may introduce more challenges than benefits. A case-by-case assessment is necessary to determine its true value.

Although blockchain presents multiple benefits for the construction industry, its adoption also faces several barriers and risks including legal, organizational, and technological barriers (Wu et al. 2023). The integration of BIM and blockchain is posing challenges such as the poor adoption of novel technologies in the industry; lack of skills; interoperability, privacy, and security risks; and blockchain scalability problems (Li et al. 2019). Because the amount of information is constantly growing during the building life cycle, the scalability of blockchain solutions is an important factor to consider. To address this issue, the use of decentralized storage, such as the IPFS, was proposed in this study. It is a common solution to the scalability issue proposed in the current literature on information management in the construction sector (Darabseh and Martins 2021; Das et al. 2022; Tao et al. 2021).

Furthermore, using a public blockchain raises concerns about the confidentiality of sensitive information (Perera et al. 2020). One approach to address this issue would be to encrypt the data stored on the IPFS to prevent unauthorized access (Naderi et al. 2023). Alternatively, private and consortium blockchains can be considered. Some authors claim a clear advantage of using a private blockchain network like Hyperledger in the construction industry because it is characterized by high data privacy and confidentially required to store sensitive construction data (Perera et al. 2020; Yang et al. 2020).

One of the fundamental questions in developing a blockchain-based solution is which blockchain architecture is the most suitable for a chosen application. For a CDE platform, this question requires an analysis of the requirements and features of both public and private blockchains, which was not conducted in this study. Ideally, proofs of concept should be developed and evaluated through case studies to validate their usefulness in a real-world context. Moreover, it should be investigated whether it is feasible to preserve the use of current cloud-based data repositories in combination with blockchain or if the integration of IPFS with current CDE platforms is more advantageous.

Conclusion

A CDE is a base of information management in a BIM-based collaboration process as defined by the ISO 19650 standard. However, current CDEs still do not serve as a single source of truth for all project information because multiple CDEs are usually used simultaneously, leading to a lack of transparency and integrity. Moreover, using cloud-based CDE platforms raises concerns about data security, data ownership protection, and lack of trust among the stakeholders. Such centralized solutions are not well-suited to the fragmented nature of the construction industry, and new more decentralized approaches should be investigated. The first step of this study was to identify the user requirements for a CDE through a literature review and semistructured interviews with industry professionals. Based on those, a conceptual framework for decentralized information management along a built asset's entire life cycle was developed.

This research contributes to academic knowledge by offering insights into the practical adoption of CDEs and blockchain's applicability in construction. Furthermore, it presents a framework, and three use-case scenarios, adding to the theoretical knowledge base of information management systems in construction. The proposed decentralized CDE, tailored to evidence-based user requirements, is a novel addition to the existing body of literature. The proposal is relevant to both academia and industry because it reflects the current state of the construction sector.

The findings of this study imply that blockchain technology has the potential to alleviate some of the problems of information management practices and provide a solution to the needs of the users. One of the top requirements for a CDE is to provide a single source of truth and integrate the data from multiple CDEs used currently in the industry. Blockchain was proposed as a suitable solution to provide this integration because it enables an immutable, independent, and reliable record of all transactions between different tools along the whole life cycle of a built asset. Blockchain is a vendor-neutral and sovereignless technology, meaning that data from all different data sources could be integrated into one place without a need for a central authority or a third party. A blockchain-based CDE would increase the accountability and traceability of information and provide trust in data accuracy among project stakeholders because tampering with data would be not possible. Linking the record of transactions with a distributed storage system such as IPFS would additionally increase the security of the files and protect against tampering with data.

Data Availability Statement

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

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Supplemental Materials

Supplemental Materials associated with this article are available online in the ASCE Library (www.ascelibrary.org).

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