Decision-making framework for implementing blockchain in building operations and maintenance (O&M)

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ABSTRACT

Blockchain is a distributed ledger technology that verifies and records transactions simultaneously across a computer network, offering data dependability, traceability, and immutability. It has gained attention in the Architecture, Engineering, Construction, and Operations (AECO) industry. However, to justify its deployment costs, it is essential to identify where blockchain can generate the most value. This study proposes that the operations and maintenance (O&M) phase of a building's life cycle, which has a significant environmental, social, and economic impact, can yield a higher return for blockchain. A literature review was conducted to investigate the implementation of blockchain in AECO, revealing a need for more attention to O&M. Inspired by the insights from the review and existing blockchain deployment frameworks, a high-level decision-making framework for blockchain adoption in O&M was developed. The paper also discusses various opportunities, challenges, and future research questions for a successful implementation of blockchain in buildings' O&M.

INTRODUCTION

Blockchain is a digital distributed ledger technology where transactions are recorded and verified simultaneously across a network of computer nodes as interlinked and interfering data blocks – thus offering data dependability, traceability, and immutability (Li et al. 2019). Transactions are authenticated through a cryptographic consensus method, managed by exchanging a token (Li et al. 2019). Those can vary according to the blockchain network. Beyond the well-known Bitcoin blockchain and its proof-of-work method (Nakamoto 2008), other consensus protocols include proof-of-stake, -authority, -importance, delegated proof-of-stake, ripple consensus, and stellar consensus (Wadhwa, 2022). Each can serve different levels of blockchain decentralization – from fully decentralized public (permissionless) to partially decentralized private (permissioned) blockchains – and facilitate networks suitable for different applications (Wadhwa, 2022).

After its introduction in 2008 by Nakamoto, blockchain has caused a stir, particularly in the FinTech industry. Nonetheless, it is mainly after 2015 that its potential for the Architecture, Engineering, Construction, and Operations (AECO) industry has gathered more interest. To date, this has culminated in concepts, prototypes, pilots, some (albeit few) use cases (Kifokeris and Koch 2022), and relevant professional and research networks (e.g., the Construction Blockchain Consortium). Nevertheless, the technology is still nascent in AECO.

Blockchain has been claimed to have the potential to alleviate some of AECO's long-standing issues (e.g., increasing trust, transparency and provenance, automation in contract management and payments, removing gatekeepers, improving digitalization and inclusivity with P2P transactions) (Li et al. 2019). However, the conceptual understanding of a digital AECO future through (blockchain) technology often outstrips practical, technical, commercial, cultural, and organizational constraints (Sacks et al, 2020). Beyond the hype surrounding it, blockchain adoption is ultimately an investment decision. As such, its deployment cost must be justified by the qualitative/quantitative benefits accrued from it. To avoid low return, "sake of" adoptions, it is important to pinpoint where blockchain can generate the most value with solid justifications, and how this value can be realized for a grounded start for the early adopters.

To commence the tackling of this question, this paper posits that a higher-potential starting point for blockchain adoption can be the operations and maintenance (O&M) phase of a building's life cycle. O&M also offers the space for implementing technologies and concepts which can be facilitated by blockchain - e.g., the Internet of Things (IoT), digital twins (DTs), or real-estate tokenization. It should be noted that this paper focuses on the O&M of buildings, as they constitute most of the built environment.

The rest of the paper describes the justifications for these claims, and outlines some key opportunities, challenges, and research questions to be investigated in the future with a high-level decision-making framework associated with blockchain for building operations and maintenance.

LITERATURE REVIEW

In AECO, early blockchain-related research tended to be highly conceptual and speculative (Xu et al. 2022) – e.g., see Cardeira (2015). In this vein, more elaborate studies have mostly been published after 2019 (e.g., Kifokeris and Koch 2022, Xu et al. 2022). For example, the suitability of different consensus protocols for various AECO-related scenarios and stakeholders can change (Xu et al. 2023a). Regardless, blockchain applications supporting an even partial decentralization can be favored over fully centralized databases when high trust levels, data security, immutability, transparency, and multi-user consensus are needed (Xu et al. 2023b). These applications typically utilize smart contracts [i.e., programs stored on Turing-complete blockchains that can automate the enforcing of terms and clauses (Ameyaw et al. 2023)] or digital tokens signifying value or ownership (Scott et al. 2021).

Given the aforementioned attributes and characteristics, the current state-of-research poses that blockchain can potentially create value for the following AECO fields: Contract management (Liu et al. 2023, Zhang et al. 2023), project information management and intelligent systems (Xu et al., 2022); procurement, supply chain and logistics management (Yoon and Pishdad-Bozorgi 2022, Elghaish et al. 2023); on-site and industrialized construction processes (Lee et al. 2023, Xu et al. 2023b); project lifecycle management (Xu et al., 2022), stakeholder management (Xu et al., 2022); and decentralized autonomous organizations (DAOs) (Lombardi and Dounas 2022), focusing on data governance issues (Hunhevicz et al. 2022) and crypto-economic models for AECO (Dounas et al. 2022)

It is likely that more innovative uses of blockchain for AECO will emerge by integrating it with other digital technologies, such as big data (Liu and Zou 2019), augmented/virtual reality

(AR/VR) technologies (Bhattacharya et al. 2021), IoT (Elghaish et al. 2021), artificial intelligence (AI) (Adel et al. 2022), BIM (Elghaish et al. 2023), and digital twins (DTs) (Jiang et al. 2023, Zhao et al. 2023). For BIM, blockchain can improve the data provenance in collaborative models (Liu et al. 2019, 2023). It should be noted that according to Nguyen et al. (2019), most blockchain applications (incl. their integration with other technologies) are still technologically immature concepts or prototypes. Commercialization for most applications is not expected before 2025 (Nguyen et al. 2019).

Those studies show that blockchain exhibits attributes that can enhance the value in AECO business models, organizations, and stakeholder roles. However, as noted earlier, there has been a heterogeneous focus on its technological characteristics. Therefore, before deciding on using blockchain, it is recommended to assess blockchain suitability for a particular transaction (Mulligan et al., 2018). With Bitcoin, blockchain was originally proposed as a public permissionless system with its benefits and limitations (e.g., long data recording times, limited scalability, and data recording capacity etc.). In time, more controlled blockchain arrangements have emerged, likening it also more to a distributed database, overcoming some of its original limitations while compromising some of its original benefits (e.g., extensive transparency and security, direct P2P transacting etc.). This complexity necessitates suitably defining the blockchain architecture (e.g., permission levels, data to be written on/off (block) chain, proof-of-work algorithm etc.) for a particular transaction for achieving the expected value (Hunhevicz and Hall 2020). Finally, research on blockchain shows that legacy IT systems, organizational and business processes, human resources, contractual and commercial arrangements should be blockchain-ready for real-life implementation (Tezel et al. 2021).

Considering the above, an AECO context in which implementing blockchain would generate high value should be sought. A building's O&M phase (incl. refurbishment, retrofitting and demolition) (Yates 2014) could be such a high-value potential context, as it is where most of a building's environmental, social, and economic impact is materialized (Zhou et al. 2023), and most associated costs are spread with multiple stakeholders and data types to be managed over a long period of time (Weeks and Leite 2022). This suits well with the blockchain promise of recording multi-party transactions requiring consensus (e.g., commercial transactions) securely and authoritatively long-term. Incidentally, the requirements and expected value of adopting blockchain in O&M is one of the least researched topics in AECO. Some studies do have a longer temporal dimension when considering a construction project's lifecycle (Xu et al. 2022, Elghaish et al. 2023); others offer concepts tackling specific issues, such as the blockchain-based IoT system for personalized indoor temperature control in Jeoung et al. (2022), and try to approach that phase through an interconnection of blockchain with technologies that can be implemented in O&M (like DTs in Jiang et al. 2023, and Zhao et al. 2023). Nonetheless, those studies mainly adopt a technological lens, rather than considering business and/or stakeholders' relationships criteria specific to O&M.

RESEARCH METHOD

A systematic literature review (Webster and Watson 2002) was performed to map blockchain implementation in AECO, qualitatively capture the lack of focus on O&M and find the existing blockchain deployment decision-making schemes for inspiration. With those findings, the framework and discussion points of the current study were drawn inductively (Bell et al. 2019).

DECISION-MAKING FRAMEWORK

The decision-making framework for implementing blockchain in buildings' O&M is depicted in Fig. 1 as a swimlane process flow graph and is conceptually based on a pragmatic combination of the World Economic Forum's framework for informing a business adoption of blockchain (Mulligan et al. 2018), Pedersen et al.'s (2019) ten-step decision path for appraising the need of implementing blockchain, and Hunhevicz's and Hall's (2020) decision framework for blockchain design options in AECO. Those frameworks approached blockchain as a general implementation option, with only Hunhevicz's and Hall's (2020) being AECO-specific. Nonetheless, even the latter did not focus exclusively on O&M. As such, we considered O&M-specific factors (e.g., in Yates (2014) and Weeks and Leite (2022)) to contextualize the framework below.

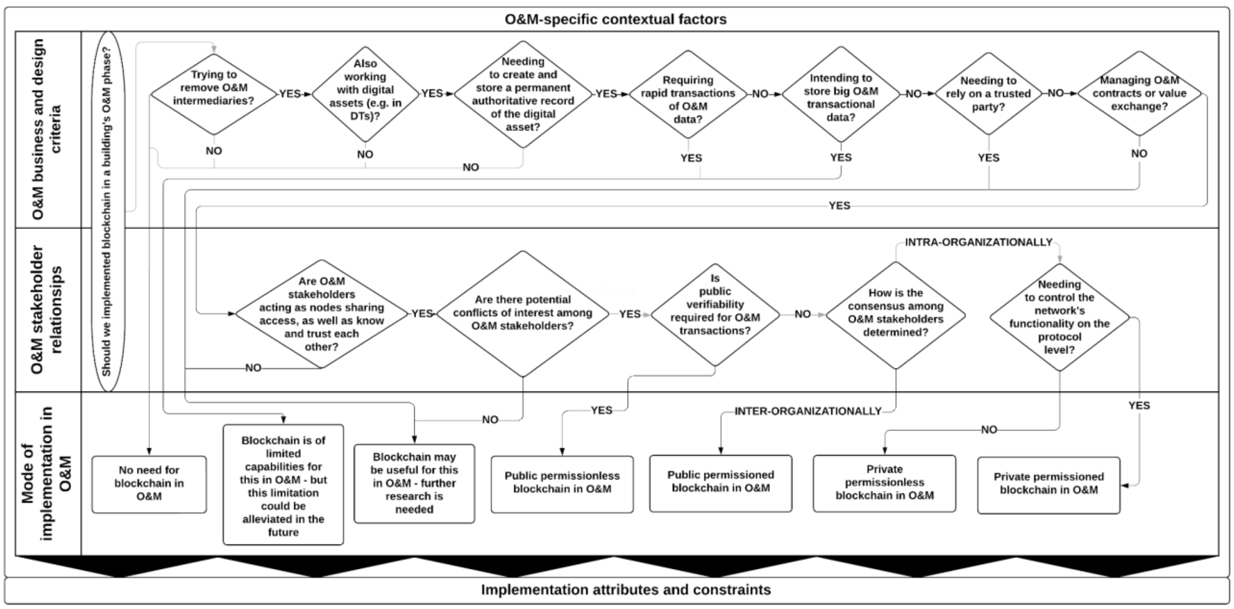

Figure 1. Decision-making framework for implementing blockchain in a building's O&M

In the framework, the O&M-specific contextual factors indicatively include the building type and its intended use; the stakeholders, users, organizations and workers involved in O&M; the specific O&M regulatory framework (incl. maintenance certifications and training); O&M human, material and monetary resources and costs; institutional considerations such as the building's environmental, social and economic impact, as well as the industry context; and the different data types associated with O&M, such as data on building attributes (e.g., numerical data for building size and energy consumption, or categorical data for building location and function) (Suliyanti and Sari 2020), sensor data on various aspects of building performance (e.g., temperature, humidity, lighting, occupancy) (Jia et al. 2021), and financial data (e.g., numerical data for operating costs or maintenance expenses, or categorical data for expense types) (Scott 2016, Yoo 2017).

Then, the lanes of the graph indicate the major dimensions to be considered, as well as the corresponding control nodes. The O&M business and design criteria for blockchain implementation concern requirements and decisions to be made about business aims and needs, the use of assets (e.g., the duality of physical and digital assets in DTs for O&M), attributes of data transactions, and the value flow through the O&M phase. Most decisions in this layer may point to blockchain not being needed in the first place, which shows that a business- and requirements-driven approach can help avoid the technology's implementation as a fad. Going into the next lane, most non-blockchain options are surpassed and the potential for blockchain implementation has emerged. There, the O&M stakeholder relationships are tied with decisions regarding possible blockchain network's issues of governance, trust, conflicts of interest, verifiability, consensus and functionality. Finally, in the implementation lane, different blockchain topologies are proposed, based on the decisions made in the preceding two layers. It is evident that most business- and design-related decisions can potentially lead to either the no-blockchain option, or an outlook of limited blockchain capability, or a potential that may be realized in the long-term. If all of those options are avoided, the business and design considerations will have led to decision nodes tied to the O&M stakeholder relationships, which can in turn point to blockchain topologies of different decentralization levels and different functionality and consensus configurations. Those can include, from the most decentralized to the most centralized, public permissionless, public permissioned, private permissionless, and private permissioned blockchains.

Finally, attributes and constraints to consider after choosing the mode of implementation can indicatively include the throughput (system processing rate), data storage in connection to its type, system interoperability, privacy concerns, smart contracts' architecture, and system cost structure (Mulligan et al. 2018, Hunhevicz and Hall 2020). Those constraints can differ depending on the implemented blockchain topology. For example, smart contracts are generally unable to function on a public permissionless blockchain, which in turn means that only simple O&M transactional actions can be recorded on such a system – like P2P payments. Similarly, macro level constraints such as organizational and business readiness, human resources, legacy IT systems' readiness, and legal and contractual readiness should be considered here.

The suggested decision-making framework offers only a high-level roadmap. It proposes starting points of consideration, which should however be much more deeply scrutinized in practice. For example, the constellation of O&M stakeholders may shift along the O&M phase of the building, especially if the latter changes use in its lifetime – like in the case of heritage buildings. Moreover, the importance of the implications of business-related decisions cannot be overstated. Those implications concern not only the initial investment of implementing blockchain in a building's O&M but have also far-reaching consequences stretched along that phase.

DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

To justify the deployment cost of blockchain, it is important to identify the areas where it can generate and realize the most value. This study suggests that the operations and maintenance (O&M) phase of a building's life cycle can be an ideal starting point for blockchain adoption in the AECO industry. A decision-making framework for blockchain adoption in O&M was developed using the existing frameworks as its basis, which can help organizations evaluate the potential benefits of blockchain adoption in O&M and make informed investment decisions.

From the interim outcomes discussed in this paper, several research limitations and future works can be suggested. The suitability of different types of O&M data transactions for recording on blockchain varies depending on the building type. For example, in large and complex buildings there may be more potential for using blockchain to record maintenance and repair data, while in smaller buildings energy usage data may be a more suitable application. This points to a need for understanding what O&M data transactions are more suitable for blockchain for different building types. Similarly, more research into improving the general readiness of the O&M stage for blockchain-based transacting is necessary.

In addition, the architecture of a blockchain system also needs to be tailored to the specific types of O&M data being recorded and the characteristics of the stakeholders involved. For instance, the architecture for recording maintenance data may differ from that for recording energy usage data, and the needs of building owners, facility managers, and service providers may also vary. Additionally, the adoption of blockchain in O&M transactions can have a significant impact on the design, construction, manufacturing, logistics, and supply chain arrangements. Therefore, early decisions on the adoption of blockchain in certain O&M transactions need to be made with careful consideration of these factors. This points to a need for a better understanding of more suitable blockchain architecture arrangements for different O&M data types and stakeholder characteristics. Similarly, the effect of early decisions on adopting blockchain in certain O&M transactions on project delivery arrangements should be investigated.

It is envisioned that in the future there will be blockchain arrangements started in the pre-design, design and construction phase of a building that will need to be handed over to the O&M phase. The question then becomes how to realize the "blockchain handover" for the O&M phase for transactions recorded in the previous stages from a technical, business process, and contractual and legal perspective.

The blockchain ecosystem and its supporting technologies are fast evolving. For instance, the emerging P2P and decentralized data storage protocols (e.g., the Interplanetary File System, or IPFS) can increase the data storage capacity of blockchain arrangements by working in tandem with it (e.g., blockchain referring to a high-resolution O&M related photo stored on IPFS). This will ultimately affect the decisions on adopting blockchain. As such, decision making frameworks for blockchain should be reviewed frequently to keep up with the changes.

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