A CONCEPTUAL FRAMEWORK FOR BLOCKCHAIN AND AI-DRIVEN DIGITAL TWINS FOR PREDICTIVE OPERATION AND MAINTENANCE

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Abstract

Digital Twins (DTs), enriched with Artificial Intelligence (AI) and Blockchain technology, promise a revolutionary breakthrough in smart asset management and predictive maintenance in the built environment. This study aims to portray a conceptual framework of Blockchain and AI-based DTs and outline its key characteristics, requirements, and system architecture by composing a functional model using IDEF0. Such an approach is expected to enhance predictive maintenance in building facilities, simplify the management and operation of smart built environments, and ultimately deliver valuable outcomes for facility operators, real estate practitioners, and end-users.

Introduction

A thorough description of the asset performance and the historical records, as well as the use of various technologies and devices, are critical to fulfilling smart asset management in the built environment, particularly regarding operation and maintenance (O&M) as a highly complicated phase. Although various tools and systems have already been created to improve O&M management, such as Building Automation Systems (BAS) and Computerized Maintenance Management Systems (CMMS), it is evident that there is a need for an integrated platform to manage data scattered across numerous databases and to support various O&M activities (Lu et al., 2020).

Predictive maintenance as a robust and efficient maintenance strategy offers an opportunity to considerably mitigate the O&M costs of different types of assets and installation in the built environment. It is an intricate data-driven procedure that aims to predict how the assets will behave in their lifecycle. On the one hand, it calls for component condition monitoring at the machine level, while the obtained data must, on the other hand, be integrated with other information management systems. The emergence of big data analytics and digitization, in particular, present great potential for developing efficient smart monitoring and predictive maintenance solutions (Katona and Panfilov, 2018). Therefore, predictive maintenance focuses on processing the operating data gathered by sensors using machine learning algorithms and data analytics approaches to identify abnormal behaviors well before a breakdown occurs. This strategy gives a chance to bridge the maintenance practices gap by assisting the facility management teams in taking swift action and preventing unanticipated failures without the need for expensive, time-consuming and intensive site investigations of the installations (Bouabdallaoui et al., 2021; Villa et al., 2021).

Due to their capacity to improve collaboration and information sharing across the project lifecycle, from the design through the O&M phase, Digital Twins (DTs) have seen an increase in acceptance by the building industry globally. However, there is a lack of evidence supporting such acceptance, particularly for facility management tasks carried out throughout the O&M phase. With the help of DT technologies, physical assets could be quickly and easily mapped to the digitally integrated platform using low-cost smart sensors, Internet of Things (IoT) devices, blockchain, big data analytics, artificial intelligence (AI), machine learning (ML), and other intelligent functions to assess the situation and real-time status of the assets. Common Data Environments (CDEs) can also be utilized to provide a quality data interchange and a bi-directional dynamic flow of information between physical and digital assets (Zhao et al., 2022). Hence, these enablers are integrated by DTs into their sub-DTs to create digital models that can learn from a variety of sources, be updated, and accurately and timely represent and predict the current and future condition of their physical counterparts. This study aims to address the insufficient process integration of blockchain technology and DTs in the built environment through a graphical representation approach. Hence, it seeks to develop a comprehensive framework that will integrate these disruptive technologies to enable predictive maintenance by providing real-time data tracking, secure storage and sharing of information, and automated execution of maintenance tasks, leading to cost savings, increased efficiency, and improved building performance. In the following sections, the research method is described in detail. This includes the implementation of function modeling as the specific technique to generate results. These results are then presented and discussed in terms of their implications and contributions to the field. Finally, the article concludes with a summary of the main findings. Through this approach, the article offers insights into the development efficient asset maintenance framework based on the current state of knowledge in the field.

Method

Any practical management system should be built on an understanding of the specifics of the process. IDEF0 (PUBS, 1993) is one of the approaches that may be used to explain manufacturing processes and can offer a way to communicate complicated ideas simply by using boxes and arrows. IDEF stands for ICAM Definition for Function Modeling, while ICAM is an acronym for Integrated Computer-Aided Manufacturing. (Alizadehsalehi and Yitmen, 2021; Waissi et al., 2015). This diagramming approach is used to describe representations of functions in complex systems, allowing the system's goal and views to be stated as well as the functional context and flows. It also seeks to conceptualize a system and its scope, constraints, and interconnections, through studying the primary functions and stakeholders (Manenti et al., 2019). However, IDEF0 only conceptualizes the process and function operations and does not represent their timing or order (Bridgeland and Zahavi, 2009).

In order to investigate a function, the IDEF0 approach takes into account four arrow classes, referred to as ICOM, that represent Inputs, Controls, Outputs, and Mechanisms/Resources (including Call arrows). Herein, *input* arrow pointing into the box from the left side, signifying data or objects to be entered into the function. The right side of the box is connected to the *output* arrow, which is pointing outward and represents the data or objects that are produced when the function is executed. *Control* arrow, attached to the top of the box and pointing inside it, indicating conditions, rules, or limits placed on the function. *Mechanism* arrow, pointing into the box from the bottom side, represents the tools and resources needed to carry out the function. *Call* arrow, attached to the bottom side of the box and pointing outward, indicates information and data sharing (or model connecting) based on an external or internal call, which is a reference to another model (Waissi et al., 2015). This study has tried to identify the IDEF0 model configuration and its components by exploring the recent literature and considering the opinions of experts in the field, captured in studies prior and relevant to this research. The findings derived from the literature review reveals a pressing need for fusion of the disruptive technologies and developing more practical integration approaches exploring and validating their true capabilities. The review also highlights the potential benefits of incorporating these technologies in addressing the implementation challenges encountered independently (Sadri et al., 2023). In the other pertinent research, the primary classifications and attributes of data, as specified by asset information requirements (AIR), are delineated, and the ways in which they can impact the creation and upkeep of an asset information model (AIM) for a blockchain-base DT are elucidated. (Hellenborn et al., 2023).

Functional analysis results

The overarching view and the components

Taking advantage of IDEF0 in this study, the process of developing a blockchain-based DT framework for smart and secure asset management is delineated. Figure 1 depicts the primary function (node A0) and summarizes its ICOM.

In an overall view, in order to develop a smart and secure asset maintenance framework, as-built models of buildings fed with real-time data form IoT devices and sensors as well as the intended maintenance plans form the departure point. Building maintenance plans offer a strategy to schedule activities to maintain the assets and monitor the progress. A well-designed and implemented strategy ensures less disturbance, fewer emergencies, and simpler repairs across the building lifecycle, ultimately leading to end-user satisfaction (Assaf and Srour, 2021). The discussed framework is expected to handle the data in a safe manner and yield real-time performance optimization of the assets through autonomous fault detection and notification.

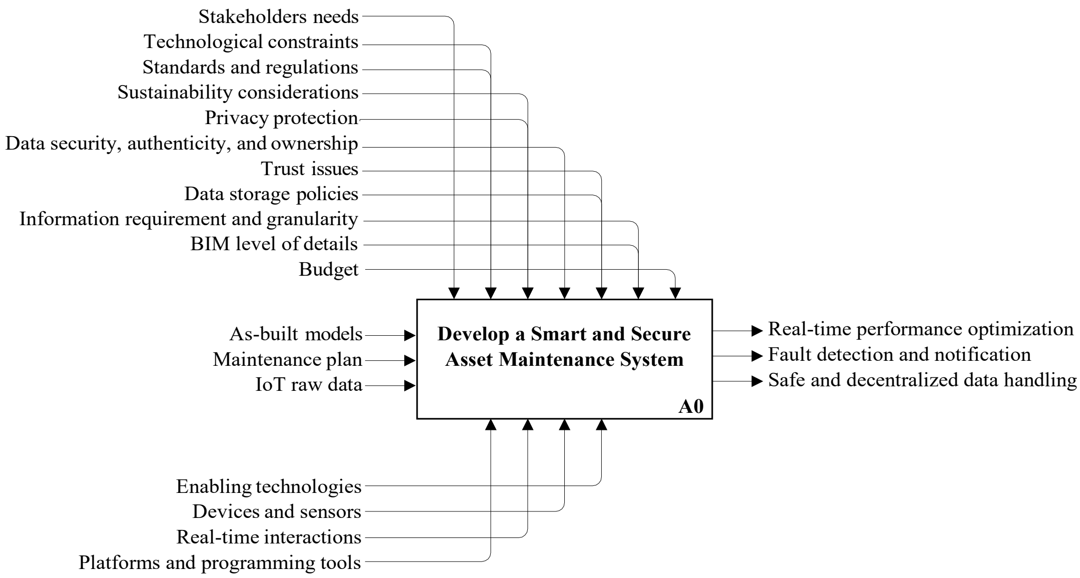

Figure 1: The primary function, overviewing the framework development requirements.

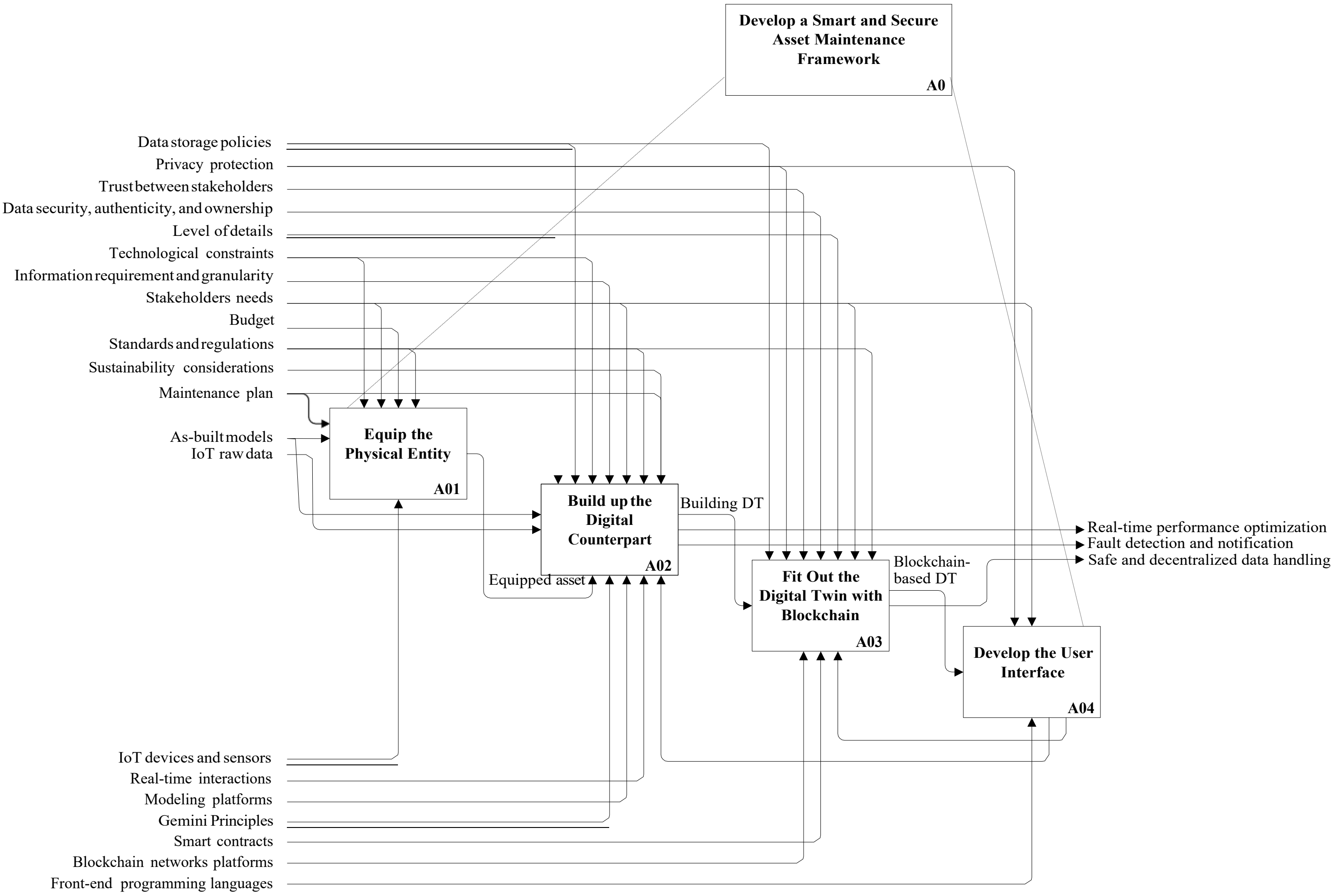

Figure 2. Decomposition of the primary function.

For this purpose, the implementation of multiple disruptive technologies and the use of appropriate platforms and programming languages to develop the required software and hardware, as well as the required devices and sensors for data collection serve as the considered mechanisms. On the other side, the process of framework development is regulated based on its usage intention, characterized by, among other factors, the needs of the stakeholders, the information requirements and the level of details in building information models (BIMs). Moreover, the availability of funds, compliance with the relevant standards and regulations, sustainability issues, and the data sensitivity and the way they should be handled are other determining considerations.

Node A0, as a parent function, is decomposed to four child functions elaborating how to equip the physical entity (node A01); build up the digital counterpart (node A02); fit out the DT with blockchain (A03); and develop the user interface (node A04), portrayed in Figure 2. At the next level, the decomposition of nodes A02 and A03 provides more details about how the DT is formed and then empowered with blockchain technology.

Decomposition of the DT development function

As illustrated in Figure 3, acquire data (A021); process the data (A022); develop models and algorithms (A023); and conduct analysis and control (A024) are the child functions of A02 as the parent. As-built models and IoT data are the inputs in this process, where the sequence of the child functions, based on the considered mechanisms and controls, results in development of the building DT, fault detection and notification in the asset, and real-time performance optimization.

In built environments, resilience in the dynamic changes of the assets and their conditions is a criterion in determining the operability of automated sensing systems. The advent of IoT technologies has opened the door for a new paradigm that focuses on creating smart devices with sensing, identification, and communication capabilities within various semi-automated and manual facility systems (A. Verma et al., 2019). The utilization of IoT

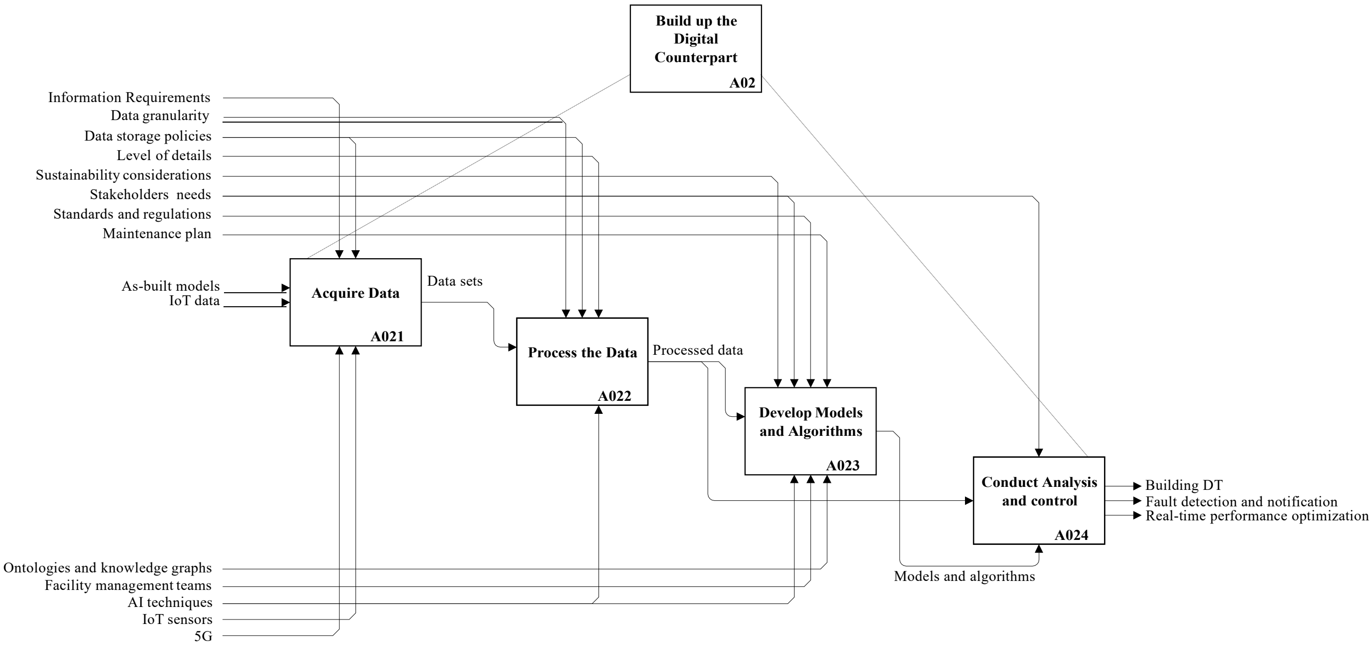

Figure 3. DT development function and its embedded sub-functions.

devices is demonstrated by existing research studies based on the devices' intended use and applications. Gathering data about the particular parameter for which a sensor was initially installed is among the decisive factors in the selection of sensors (Gao et al., 2021). In this way, the emergence of the fifth generation of cellular mobile communications (5G) is milestone in evolution of IoT utility. This is primarily because 5G networks will significantly boost the functionality, reliability, and accuracy of these connected devices.

The use of smart devices and sensors to gather information and carefully monitor the built environment will eventually result in the collection of a vast volume of raw data (also known as big data), which is practically impossible to align, annotate, and analyze manually and using conventional techniques (Wang et al., 2022). This is where computational and cognitive approaches come into play. These solutions can contribute to cleaning and processing the accumulated raw data conforming to the expected level of detail and developing effective models and algorithms accordingly. Furthermore, ontologies and knowledge graphs (KGs), as a facilitating mechanism, would manage data, information, and knowledge by integrating them into comprehensible graphical structures. They provide semantic descriptions of related objects, events, and concepts. The early extracted knowledge needs to be integrated (known as knowledge fusion) and standardized through ontology schema, as it can be preliminarily redundant and erroneous. Additionally, techniques for knowledge augmentation and quality evaluation refine KGs. For proactive inquiries and unusual responses, KG can infer workable solutions using semantic entities and edges (Xia et al., 2022).These techniques can also prevail over the limitations of IoT networks by spotting patterns and abnormalities and making predictions relying on the vast amounts of data collected by IoT network devices and sensors (Chanal et al., 2021). AI has the potential to increase cost estimate accuracy during the O&M phase and reduce operational risks by applying constructive alternative analysis to analyze and control the information flow and asset behavior (Regona et al., 2022).

Blockchain integration function breakdown

By the same token, and as shown in Figure 4, function A03 is broken down to three child functions, namely organize the data and model (A031); store the raw data off-chain (A032); and store the processed data on-chain (A033). Consistent with the defined mechanisms and controls, these functions receive the DT generated in function A02, and yield a blockchain-based DT system as well as classifying the data as on-chain and off-chain.

Managing data in blockchain-based solutions is basically performed using on-chain and off-chain storage methods. On-chain data management refers to events that are reflected in the blockchain network and result in an update of blockchain status to verify and ensure the validity of data transfers. On the contrary, off-chain data handling indicates data storage and transmission outside the blockchain network, somewhere such as external databases or cloud systems.

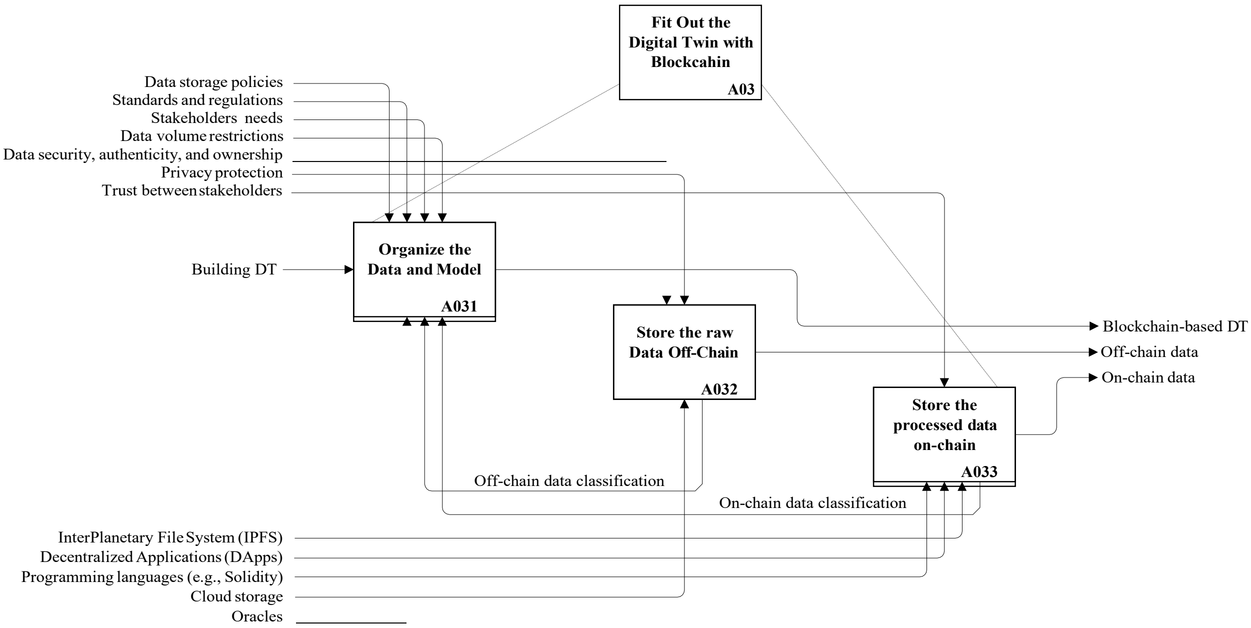

Figure 4. Breakdown of blockchain integration function.

In this framework, building DT is the input to A031, while the sorted data classifications along with oracles, as the connection points between on-chain and off-chain data, provide the mechanisms. InterPlanetary File System (IPFS), as a peer-to-peer protocol for distributed file storage and retrieval, also allows for faster and more efficient data transfer (Kumar and Tripathi, 2020) while decentralized applications (DApps) can be used to store, share and access data in a decentralized and secure way (Figueroa et al., 2019). However, the deployment and ongoing management of self-managed nodes are frequently challenging. Therefore, the proposed framework in this study can adapt, for instance, Google Cloud's Blockchain Node Engine (BNE) as a host for the nodes in the network. This fully managed node-hosting service can reduce the need for node operations, relay transactions, and read/write blockchain data with the anticipated reliability, performance, and security from Google Cloud computing and the network infrastructure (Zavery and Tromans, 2022). Furthermore, since Ethereum, which is the blockchain that has introduced smart contracts is also supported by BNE, this platform is seen as a beneficial means to facilitate the deployment of performance-based smart contracts.

Discussion

This study attempts to introduce a conceptual framework, which is seen to enable the built environment management and maintenance in a more smart and effective way, through the integration of disruptive technologies including digital twin, AI, IoT, and blockchain technologies. As depicted in figure 5, IoT devices would be deployed throughout the physical asset to collect data on its condition and performance. DT, as the core of this framework, is on the one hand, connected with the physical counterpart to exchange real-time dynamic data, and on the other hand, using AI algorithms processes the raw data to provide intelligent models for smart management of assets. The asset's real-time data, together with other static data, core data, and the as-built models would be stored on cloud storage as a scalable container for large amounts of data (Abdelrahman et al., 2020). However, IoT data transmission and storage processes relying on cloud storage systems have issues such as low data credibility, single point of failure, and malicious manipulation or data theft (Li et al., 2022; Zhang, 2021).

AI algorithms as well as available ontologies and knowledge graphs could be used to analyze the accumulated data and make decisions accordingly, enhancing the building performance such as the operation of Heating, Ventilation and Air Conditioning (HVAC) systems or predicting maintenance needs (Kwon et al., 2020; Regona et al., 2022).

The use of blockchain in this context can bring trust, transparency, immutability, and seamless authentication to the data records (Fernández-Caramés and Fraga-Lamas, 2018), through filing a decentralized record of the essential data as well as a log of the activities, maintenance progresses, and changes effected to the asset. Furthermore, smart contracts, as self-executing contracts with the coded terms of the agreement between the actors, can be enforced on blockchain (Wang et al., 2021). Smart contracts as well as blockchain-based DApps can automate the process of data validation, effectuate performance-based payments, and reduce the need for intermediaries and manual intervention (Shen and Pena-Mora, 2018; Tian et al., 2020), which can effectively save time and costs.

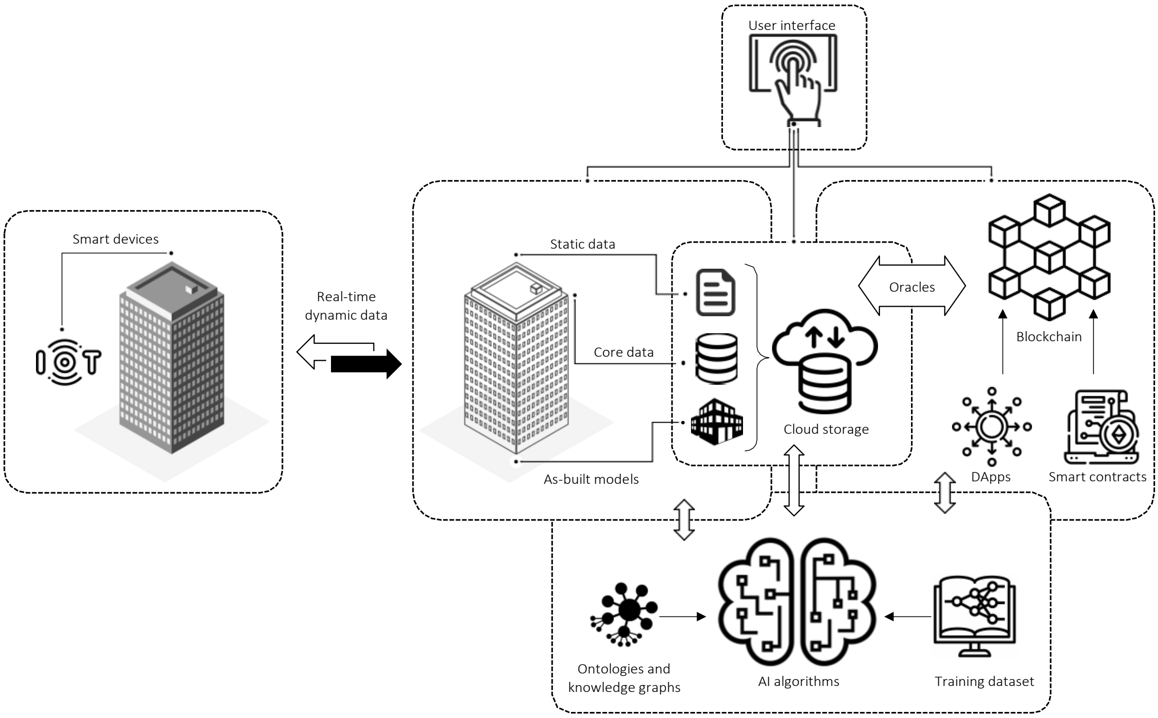

Figure 5. A conceptual framework of Blockchain and AI-based Digital Twins in the built environment.

At the same time, oracles, as third-party services, would be used to link the data stored in the cloud to the blockchain. This would allow for validating and verifying the external data, which are maintained off-chain due to the scalability issues of blockchain. Such oracle-based collaborative control mechanism between on-chain and off-chain data can safely and efficiently address the credibility issues in massive data management and interaction (Weixian et al., 2021).

This integrated framework would allow for improving the accuracy and effectiveness of the digital twin, enabling real-time monitoring and better decision-making and management of the physical asset, prediction of future performance and maintenance demands, as well as the data transaction in a tamper-proof and transparent way.

Conclusion

The use of DTs in smart asset management and predictive maintenance is seen as a revolutionary breakthrough in the built environment. This study aimed to introduce a conceptual framework for Blockchain and AI-based DTs in the field. The proposed framework outlines the key characteristics, requirements, and system architecture of DTs using IDEF0 functional modeling, to clarify how the integration of technologies such as IoT devices, big data analytics, and machine learning into DTs allows for the real-time monitoring and assessment of physical assets and can then be used to predict potential failures and mitigate maintenance costs. IDEF0 provides a structured and standardized approach for modeling complex systems, which can help to identify inefficiencies, recognize the critical paths and bottlenecks in the process, and ultimately lead to the. development of more efficient systems.

Predictive maintenance is a pivotal aspect of smart asset management in the built environment, and the integration of DTs with AI and Blockchain technology offers great potential in this regard. The combination of these technologies facilitates a seamless flow of information between physical and digital assets, which can be used to identify abnormal behaviors and prevent unanticipated failures.

Implementation of DTs in facility management tasks throughout the operation and maintenance phase can also improve collaboration and information sharing across the project lifecycle, which can ultimately create value for facility operators, real estate practitioners, and end users.

Although this study focuses on the potential benefits of DTs in the built environment, it is important to note that the implementation of such technology can also present certain challenges. These include the need for a robust and secure data management system, as well as the need for a skilled workforce to operate and maintain the technology. Additionally, further research is needed to explore the practical applications and limitations of DTs in the built environment.

The adoption of disruptive technologies, integrated into the conceptual framework in this study, can revolutionize the way of managing and maintaining physical assets, and ultimately result in a smarter and more efficient built environment. Hence, the future looks promising for enhanced DTs, as they present a vast array of opportunities and advantages that can be utilized to optimize and streamline the smart built environment.

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References

A. Verma, S. Prakash, V. Srivastava, A. Kumar, S. C. Mukhopadhyay, 2019. Sensing, Controlling, and IoT Infrastructure in Smart Building: A Review. IEEE Sens. J. 19, 9036–9046. https://doi.org/10.1109/JSEN.2019.2922409

Abdelrahman, M.M., Zhan, S., Chong, A., 2020. A three-tier architecture visual-programming platform for building-lifecycle data management. SimAUD.

Alizadehsalehi, S., Yitmen, I., 2021. Digital twin-based progress monitoring management model through reality capture to extended reality technologies (DRX). Smart Sustain. Built Environ. ahead-of- print. https://doi.org/10.1108/SASBE-01-2021- 0016

Assaf, S., Srour, I., 2021. Using a data driven neural network approach to forecast building occupant complaints. Build. Environ. 200, 107972. https://doi.org/10.1016/j.buildenv.2021.107972

Bouabdallaoui, Y., Lafhaj, Z., Yim, P., Ducoulombier, L., Bennadji, B., 2021. Predictive maintenance in building facilities: A machine learning-based approach. Sensors 21, 1044.

Bridgeland, D.M., Zahavi, R., 2009. Chapter 5 - Business Process Models, in: Bridgeland, D.M., Zahavi,

R. (Eds.), Business Modeling. Morgan Kaufmann, Boston, pp. 103–137. https://doi.org/10.1016/B978-0-12-374151- 6.00005-7

Chanal, P.M., Kakkasageri, M.S., Manvi, S.K.S., 2021. Chapter 7 - Security and privacy in the internet of things: computational intelligent techniques- based approaches, in: Bhattacharyya, S., Dutta, P., Samanta, D., Mukherjee, A., Pan, I. (Eds.), Recent Trends in Computational Intelligence Enabled Research. Academic Press, pp. 111–127. https://doi.org/10.1016/B978-0-12-822844-9.00009-8

Fernández-Caramés, T.M., Fraga-Lamas, P., 2018. A Review on the Use of Blockchain for the Internet of Things. Ieee Access 6, 32979–33001.

Figueroa, S., Añorga, J., Arrizabalaga, S., 2019. An attribute-based access control model in RFID systems based on blockchain decentralized applications for healthcare environments. Computers 8, 57.

Gao, X., Pishdad-Bozorgi, P., Shelden, D.R., Tang, S., 2021. Internet of things enabled data acquisition framework for smart building applications. J. Constr. Eng. Manag. 147, 04020169.

Hellenborn, B., Eliasson, O., Yitmen, I., Sadri, H., 2023. Asset information requirements for blockchain- based digital twins: a data-driven predictive analytics perspective. Smart Sustain. Built Environ.

Katona, A., Panfilov, P., 2018. Building predictive maintenance framework for smart environment application systems. Presented at the Annals of DAAAM and Proceedings of the International DAAAM Symposium, pp. 0460–0470.

Kumar, R., Tripathi, R., 2020. Blockchain-based framework for data storage in peer-to-peer scheme using interplanetary file system, in: Handbook of Research on Blockchain Technology. Elsevier, pp. 35–59.

Kwon, S., Monnier, L.V., Barbau, R., Bernstein, W.Z., 2020. Enriching standards-based digital thread by fusing as-designed and as-inspected data using knowledge graphs. Adv. Eng. Inform. 46, 101102. https://doi.org/10.1016/j.aei.2020.101102

Li, X., Lu, W., Xue, F., Wu, L., Zhao, R., Lou, J., Xu, J., 2022. Blockchain-Enabled IoT-BIM Platform for Supply Chain Management in Modular Construction. J. Constr. Eng. Manag. 148. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002229

Lu, Q., Xie, X., Parlikad, A.K., Schooling, J.M., 2020. Digital twin-enabled anomaly detection for built asset monitoring in operation and maintenance. Autom. Constr. 118, 103277. https://doi.org/10.1016/j.autcon.2020.103277

Manenti, G., Ebrahimiarjestan, M., Yang, L., Yu, M., 2019. Functional modelling and IDEF0 to enhance and support process tailoring in systems engineering. Presented at the 2019 International Symposium on Systems Engineering (ISSE), IEEE, pp. 1–8.

PUBS, F., 1993. Announcing the standard for integration definition for function modeling (idef0). Draft Fed. Inf. Process. Stand. Publ. 183.

Regona, M., Yigitcanlar, T., Xia, B., Li, R.Y.M., 2022. Artificial Intelligent Technologies for the Construction Industry: How Are They Perceived and Utilized in Australia? J. Open Innov. Technol. Mark. Complex. 8. https://doi.org/10.3390/joitmc8010016

Sadri, H., Yitmen, I., Tagliabue, L.C., Westphal, F., Tezel, A., Taheri, A., Sibenik, G., 2023.

Integration of Blockchain and Digital Twins in the Smart Built Environment Adopting Disruptive Technologies—A Systematic Review. Sustainability 15, 3713.

Shen, C., Pena-Mora, F., 2018. Blockchain for cities—a systematic literature review. Ieee Access 6, 76787–76819.

Tian, Y., Lu, Z., Adriaens, P., Minchin, R.E., Caithness, A., Woo, J., 2020. Finance infrastructure through blockchain-based tokenization. Front. Eng. Manag. 7, 485–499.

Villa, V., Naticchia, B., Bruno, G., Aliev, K., Piantanida, P., Antonelli, D., 2021. IoT Open-Source Architecture for the Maintenance of Building Facilities. Appl. Sci.-BASEL 11. https://doi.org/10.3390/app11125374

Waissi, G.R., Demir, M., Humble, J.E., Lev, B., 2015. Automation of strategy using IDEF0 — A proof of concept. Oper. Res. Perspect. 2. https://doi.org/10.1016/j.orp.2015.05.001

Wang, W., Guo, H., Li, X., Tang, S., Xia, J., Lv, Z., 2022.

Deep learning for assessment of environmental satisfaction using BIM big data in energy efficient building digital twins. Sustain. Energy Technol. Assess. 50. https://doi.org/10.1016/j.seta.2021.101897

Wang, Z., Jin, H., Dai, W., Choo, K.-K.R., Zou, D., 2021. Ethereum smart contract security research: survey and future research opportunities. Front. Comput. Sci. 15, 1–18.

Weixian, W., Ping, C., Mingyu, P., Xianglong, L., Zhuoqun, L., Ruixin, H., 2021. Design of Collaborative Control Scheme between On- chain and Off-chain Power Data. Presented at the 2021 IEEE 4th International Conference on Information Systems and Computer Aided Education (ICISCAE), IEEE, pp. 1–6.

Xia, L., Zheng, P., Li, X., Gao, Robert.X., Wang, L., 2022. Toward cognitive predictive maintenance: A survey of graph-based approaches. J. Manuf. Syst. 64, 107–120. https://doi.org/10.1016/j.jmsy.2022.06.002

Zavery, A., Tromans, 2022. Introducing Blockchain Node Engine [WWW Document]. Google Cloud Blog. URL https://cloud.google.com/blog/products/infrastructure-modernization/introducing-blockchain- node-engine (accessed 11.14.22).

Zhang, L., 2021. Research on the New Path of Internet of Things Data Mining under the Background of Cloud Computing. Presented at the Journal of Physics: Conference Series, IOP Publishing, p. 042089.

Zhao, J., Feng, H., Chen, Q., Garcia de Soto, B., 2022. Developing a conceptual framework for the application of digital twin technologies to revamp building operation and maintenance processes. J. Build. Eng. 49. https://doi.org/10.1016/j.jobe.2022.104028