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Exploring applicability, interoperability and integrability of Blockchain-based digital twins for asset life cycle management

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Abstract

Purpose – The blockchain-based digital twin has been recognized as a prominent technological ecosystem featuring synergies with both established and emergent information management practice. The purpose of this research is to explore the applicability, interoperability and integrability of a blockchain-based digital twin for asset life cycle management and develop a model of framework which positions the digital twin within a broader context of current management practice and technological availability.

Design/methodology/approach – A systematic literature review was performed to map use cases of digital twin, IoT, blockchain and smart contract technologies. Surveys of industry professionals and analyses were conducted focussing on the mapped use cases' life cycle–centric applicability, interoperability and integrability with current asset life cycle management practice, exploring decision support capabilities and industry insights. Lastly, a model of framework was developed based on the use case, interoperability and integrability findings.

Findings – The results support approaching digitization initiatives with blockchain-based digital twins and the positioning of the concept as both a strategic tool and a multifunctional on-field support application. Integrability enablers include progression towards BIM level 3, decentralized program hubs, modular cross-technological platform interfaces, as well as mergeable and scalable blockchains.

Practical implications – Knowledge of use cases help highlight the functionality of an integrated technological ecosystem and its connection to comprehensive sets of asset life cycle management aspects. Exploring integrability enablers contribute to the development of management practice and solution development as user expectations and technological prerequisites are interlinked.

Originality/value – The research explores asset life cycle management use cases, interoperability and integrability enablers of blockchain-based digital twins and positions the technological ecosystem within current practice and technological availability.

Keywords Digital Twin, Blockchain, Smart asset lifecycle management, Building information management (BIM)

Paper type Research paper

1. Introduction

Progress towards a digitalized construction industry is being fuelled by the pursuit of improved global resourcefulness, decreased environmental footprints and sustainable well-being–centric designs (Wong *et al.*, 2013; Shojaei *et al.*, 2019). Significant advances have been made within the fields of collaborative design and value-driven construction wherein the use of building information management (BIM) is widely considered a main facilitator (McArthur, 2015; Koch *et al.*, 2019). Similarly, the potential to derive profits and meet sustainability goals by digitalizing the operation and maintenance (O&M) phase has been identified as large (McArthur, 2015). Central for successful O&M is efficient management of the asset throughout its life cycle in all relatable strategic and operative aspects (Tchana de Tchana *et al.*, 2019; O'Sullivan *et al.*, 2004; Muller *et al.*, 2019). Traditional facility management is shifting towards O&M-focussed asset life cycle management as sustainability goal fulfilment becomes increasingly important for tenants and company stakeholders (Shojaei *et al.*, 2019).

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Subsequently, new smart asset life cycle management technologies have emerged (Erri *et al.*, 2019). Digital twins, Internet of Things (IoT) and blockchains have been receiving much attention for their synergic functionality with both established and emergent information management solutions. Ignoring one or the other will probably lead to a disadvantageous competitive market position (Mathews *et al.*, 2017). Digital twins provide asset managers with access to real-time, trustworthy, change-resistant records of real estate data (Macchi *et al.*, 2018). They can also allow for automated optimization protocols to be carried out and IoT connected building systems to be regulated. IoT technology is the concept of interconnected networks of communicating and sensor-data sharing devices (Moin *et al.*, 2019). Blockchains are decentralized records of data distributed and operated on peer-to-peer networks of computers. They are appropriate and useful for generating, monitoring and exchanging digital twin data due to their distinctive characteristics of auditability, security and immutability (Moin *et al.*, 2019; Deloitte, 2018). Their collective potential to align current asset life cycle management and BIM use practice with high level sustainability goals is assumed significant (Shojaei *et al.*, 2019; Macchi *et al.*, 2018). Meanwhile, the asset management sector is highly fragmented, supply chains are complex and real estate life-cycle phases are segregated (Hunhevicz and Hall, 2020). As a result, asset managers are resistant towards integrating new technologies into current management processes (ICE, 2018).

To date, the main challenge has been to standardize processes of old, renovated and newly built assets with different information structures and packaging (Ding *et al.*, 2019). BIM levels, also referred to as BIM maturity levels, are measurements of built environment supply chains' abilities to operate and exchange information as classified by Bew and Richards (2008). BIM Level 3, the top level, features asset information model (AIM) usage for life cycle asset management and integrated services for collaboration. Much progress has been made within the field of BIM and virtual reality integration for improving project communication, creativity, coordination and data integration (Goulding and Rahimian, 2012; Rahimian *et al.*, 2011; Davidson *et al.*, 2019). However, BIM and AIM integration has so far been challenging due to little focus on connecting the planning, design and construction phases with the O&M phase (Koch *et al.*, 2019). This has partially contributed to today's real estate industry merely being at BIM level 2 which is insufficient when integrating digital twins with current BIM practice (Li *et al.*, 2019a, b). Recurrent issues as of today are lacking cross-company alignment, low accuracy of data captured from "as-built" models and time-consuming maintenance of building information and IoT data. There are also limited solutions for collecting, processing and communicating information flows (Macchi *et al.*, 2018). Accelerated progresses are nonetheless being made towards BIM level 3. Moreover, with the continual introduction of new cost-efficient solutions, such as photogrammetry and laser scanning, for semi-automated building information generation the opportunity to migrate entire portfolios to a digital interface arise. The asset management industry is hence becoming increasingly interested in technological ecosystems including: digital twins, IoT networks and blockchains, which could be part of the solution for interlinking work processes, stakeholders and assets' life cycle phases (Wong *et al.*, 2018).

However, there are gaps in the current body of knowledge. A lacking number of frameworks for how to integrate emerging technologies with industry-compliant "best-practice" processes have been published (Wong *et al.*, 2018). Meanwhile, frameworks are important for guiding technological ecosystem integration. Some of the existing frameworks are a BIM-based framework for safety in FM (Wetzel and Thabet, 2015), a knowledge-based BIM system for building maintenance (Motawa and Almarshad, 2013), a combined BIM/GIS–based data integration framework enhancing interoperability of varied information from BIM, GIS and FM systems (Kang *et al.*, 2016), a collaborative BIM-based markerless mixed reality framework for facilities maintenance (Ammari and Hammad, 2014), a BIM-based decision support system framework for predictive maintenance management of building facilities (Cheng *et al.*, 2016), a spatial data framework for facility management supply chains (Karan and Irizary, 2014) and a framework for the utilization of building management system data in building formation models for building design and operation (Oti *et al.*, 2016). Efficient utilization of technological ecosystems is generally first actualized when asset management professionals receive useable and integrable solutions (Nysveen *et al.*, 2020; Mehrbod *et al.*, 2019). There is thus currently a need for a model of a Blockchain-based digital twin framework to be developed in collaboration with industry professionals. With the model of framework as a base, the next step towards filling the knowledge gap is then to develop solution-based frameworks and applying them when integrating smart asset life cycle management solutions during the progression towards BIM level 3 practice.

The aim of this study to explore the applicability, interoperability and integrability of a Blockchain-based digital twin for asset life cycle management and develop a model of framework which positions the digital twin within a broader context of current management practice and technological availability, whereas the second part includes showcasing a comprehensive set of technological use cases within the state-of-the-art asset management industry segment. In alignment with the study's aim, three research questions are posed:

(1) What functionalities do industry professionals allocate a Blockchain-based digital twin for asset life cycle management?

(2) How interoperable is a Blockchain-based digital twin with current asset management technologies?

(3) What integrability enablers are necessary for implementing the blockchain-based digital twin?

The main contribution to the knowledge domain is insight into the functionality of a blockchain-based digital twin solution and its connection to most areas of asset life cycle management during the O&M phase. Furthermore, the synthesization of industry professionals' questionnaire insights and comments further enables analysis of integrability enablers and professionals' perception of the technological ecosystem's usability. Knowledge of the interoperability potential between digital twin, IoT, blockchain and smart asset management systems could also contribute to the development of asset life cycle management practice.

Section two of this paper includes a breakdown of this study's applied research method, including a systematic literature review, surveying, statistical covariance and thematic analyses. In Section three, previous research insights are introduced together with a complete technological use-case mapping. In section four, survey findings and a model of the blockchain-based digital twin framework are presented and analysed. Section five consists of a discussion of the results, and lastly, in Section six conclusions are drawn.

2. Research methodology

There are five steps to this paper's research methodology including a systematic literature review, a quantitative and qualitative digital survey, descriptive statistics and covariance analyses, a thematic analysis and the development of the model of framework.

2.1 Systematic literature review

Initially a systematic literature review was performed to identify, evaluate and synthesise the existing body of completed and recorded work on current use cases for digital twins of sophistication level 2 or higher as defined by Madni *et al.* (2019), IoT networks and blockchains for asset life cycle management. Although smart contracts are closely related to the blockchain technology, the smart contract use cases were assigned a separate section to set apart data-storing capabilities and process automation capabilities. The scope of the review was not only limited to the O&M phase but included general applicability in the built environment. Integrating O&M management with planning, construction and demolition phases is important as it allows for digital twin and building information re-use throughout the entire lifecycle. As a result, digitization initiatives are utilized through and throughout, hence yielding topmost value. Moreover, an investigation into how smart asset life cycle management is used today and how the trend is developing was done by including papers assessing technological trends to future-proof the research findings.

To broaden the search for research papers, the identified keywords connected to the topic were translated into synonyms. The search term combinations were developed to investigate the applicability of each technology individually for asset life cycle management. The final search codes consisted of the words digital twin, Internet of Things, Blockchain and smart contract combined with the words asset, facility, building, real estate, life cycle and management. The search filters were publishing years 2019 and 2020, language English and access type Open. The search results were saved as RIS files for further processing in Rayyan.

Eight searches in two journal databases, Scopus and ScienceDirect returned 916 papers, from which 46 papers were selected for review after the removal of duplicates, inclusion and exclusion criteria application and abstract reviews as suggested in the PRISMA guidelines for systematic reviews (Moher *et al.*, 2009). Publication novelty of papers discussing digital twin, IoT and Blockchain use cases and the technologies' tie to asset management navigated the inclusion and exclusion process. 543 articles were excluded after title screening, and 54 articles were excluded after abstract screening. There were also 273 duplicates among the returned papers from Scopus as a direct result of overlapping content of technology-specific papers in which other technologies were briefly mentioned but not substantially elaborated upon. 20 more papers were excluded during the data extraction process because of the papers' lack of asset life cycle management-centric technology use-case reviews. Many of the excluded papers either focused on similar manufacturing-centric use cases or use cases which were not replicable for the development or maintenance of a building asset.

The extensive scope provided a holistic approach to the use-case mapping while maintaining distinctiveness due to the specificity of the selection. Technological use cases were then identified, coded and thematically analysed. The findings, from the review, were subsequently tabulated as shown in Table 1.

The use-cases of Table 1 are categorized on aspects of asset life cycle management which in the theoretical framework are summarized and re-categorized on technological areas.

2.2 Survey

With the literature review as a base, a digital survey as seen in Appendix was developed and sent to industry professionals internationally. The main theme of the survey was: industry professionals' perception of the mapped technological use cases' life cycle–centric applicability and integrability with current management practice. Additionally, an investigation was initiated into how pre-asset management information should be retrievable from the blockchain. This included supply chain information, provenance of materials, payment details, design decisions, source of data or model modification orders. Along with these, it had how information should be assignable to the blockchain during its operational life cycle such as renovations, tenant information and sensor data.

2.2.1 Sampling and data collection. The survey population included professionals from enterprises operating in America, Asia Pacific, Europe, Scandinavia, and the Middle East. It was limited to actors with key roles in capturing, delivering and using smart asset information as well as those participating in innovation projects within the technology

Table 1. Technological use-case mapping as tabulated in the systematic literature review

Aspects of asset lifecycle management			Technological use-cases IoT	Blockchain	Smart contract	Digital twin	References
Operations, maintenance and daily management	Facility management	(1) Workplace services (2) Scheduled maintenance (3) Occupational wellness and safety management	(1) Monitor space, light, temperature and ventilation utilization (2) Monitor water and electricity consumption (3) Monitor dynamic behaviours and smart user interactions	(1) Store operational data	(1) Automatically regulate building systems (2) Smart meter solution for water, energy and grid providers enabling decentralized trading	(1) Visualizations, simulations, and scenario generations (2) Provide information about the building's systems and products (3) Function and evolution simulations	Arslan *et al.* (2019), BIM Task Group (2011), Cao *et al.* (2020), Deloitte (2018), Minoli (2019), Parkinson *et al.* (2019)
	Operations and maintenance	(1) Janitorial and security (2) Cleaning and waste management (3) Utility, mechanical, electrical and groundskeeping maintenance (4) Unscheduled maintenance (5) Service requests (6) Emergency responses	(1) Trace movement (2) Monitor cleanliness and waste levels (3) Conditions monitoring (4) Damage and error localization	(1) Store maintenance, access, and activity metadata	(1) Automatically assign facility managers tasks (2) Tenant, work, and visitor hour registration, as well as ID verification (3) Additional work claims (4) Predictive planning for maintenance (5) Smart scheduling	(1) Dashboard for sensor and device communication (2) Provide building information (equipment health, assembly instructions, manufacturer, supply chain and warranty information) (3) Predict and coordinate maintenance work (4) Real-time support for operations and maintenance processes	Arslan *et al.* (2019), Deloitte (2018), ICE (2018), Li *et al.* (2019a, b), Love and Matthews (2019); Lydon *et al.* (2019), Manavalan and Jayakrishna (2018), Negri *et al.* (2019), Qinglin *et al.* (2019), Rashid *et al.* (2019)

(*continued*)

Table 1.

Aspects of asset lifecycle management			Technological use-cases IoT	Blockchain	Smart contract	Digital twin	References
Property portfolio and projects		(1) Space planning (2) Renovations (3) New constructions (4) Transactions	(1) Monitor space utilization, light and temperature preferences as well as productivity (2) Communicate with unmanned aerial vehicle and construction machinery	(1) Store tenant and utilization data (2) Central site information datahub (3) Provides secure and cost-effective decentralized data storage	(1) Contract regulation and compliance (2) Payments and invoices	(1) Decision support for renovation initiatives (2) Benchmarking for new constructions and asset transactions (3) Asset Information Modelling (AIM)	Arslan *et al.* (2019); BIM Task Group (2011), Heaton *et al.* (2019), Helo and Hao (2019), ICE (2018), Lou *et al.* (2019), Macchi *et al.* (2018), Moin *et al.* (2019), Parkinson *et al.* (2019), Tchana de Tchana *et al.* (2019), Zhai *et al.* (2019), Zibin *et al.* (2019), You and Wu (2019)
General administration	Economics	(1) Contract management (2) Finance and insurance controlling		(1) Store contract and economic data (2) Accelerate transaction times	(1) Automation of payment and invoice management	(1) AIM integration with financial systems provides opportunities to improve controlling practice	Heaton *et al.* (2019), ICE (2018); Moin *et al.* (2019), Zibin *et al.* (2019)
	External compliances	(1) The UN Sustainable Development Goals (2) Certifications and standards (3) National regulations	(1) Gather sustainability and wellbeing centric data (2) Real-time access to environmental conditions	(1) Store raw material, fabrication, transportation, and installation "as-assembled" data for products, materials, and installations	(1) Contract compliance among subcontractors	(1) Check goals, certifications, standards, and regulations compliances for quality assurance (2) Carbon footprint assessments	BIM Task Group (2011), ICE (2018), Li *et al.* (2019a, b), Parkinson *et al.* (2019), Zibin *et al.* (2019)

(*continued*)

Table 1.

Aspects of asset lifecycle management		Technological use-cases: IoT	Blockchain	Smart contract	Digital twin	References
Leadership, strategy and business management	(1) Performance management (2) Portfolio planning (3) Market intelligence management (4) Strategic and risk planning (5) Resource and logistics planning (6) Internal and external communication (7) Corporate social responsibility	(1) Monitor utilization and project progress generally	(1) Store performance and market data (2) Store project deliveries (3) Logging of BIM and managerial decision data	(1) Automatized administration (2) Define project teams, deliverables, and design packaging (3) Milestone and completion checking, approval and follow up (4) Cost, budget, and time monitoring	(1) Live data feed of key performance indicators, reporting and task updates (2) Decision support for strategic business planning (3) Greatly advance sustainable smart manufacturing throughout the lifecycle (4) Ensures that investments in digital technologies can effectively respond to business drivers and generate value	Battisti *et al.* (2019), ICE (2018), Love and Matthews (2019), Mathews *et al.* (2017), Zibin *et al.* (2019)

domains. A list of relevant asset management companies was put together through searches in publicly available databases cataloguing enterprises based on geographical location on country level. The sample included both asset owners and asset management consultancies. The nationwide inclusions enhance the validity of the questionnaire responses as it embodies diversity of corporate as well as national cultures, knowledge and ways of working. Table 2 shows the distributions in percentages of company roles, sizes and regions.

A total of 267 enterprises were contacted through LinkedIn, and one representative from each was invited to partake in the survey. The participants were informed of the research objectives as well as of the confidentiality and anonymity of their answers. 85 completed questionnaires were returned resulting in a response rate of 32%. The participants were asked to share information about their current role, experiences and the company they work for. They also rated their perceived agreement with digitalization-centric asset life cycle management statements as positioned on a five-point Likert scale of 1 (strongly disagree) to 5 (strongly agree). They were also presented the opportunity to explain their statement positioning and to provide additional information about their practices as well as technological ecosystems in an open-ended question section as seen in Appendix.

2.2.2 Statistical analysis. The collected close-ended question responses were analysed using the Statistical Package for Social Sciences (SPSS, version 21; SPSS, Inc. Chicago, IL, USA). Descriptive statistics reported on mean agreement ratios and standard deviations for statements about current asset life cycle management practice, technological ecosystem landscapes, technological use cases and contextual integrability enablement as well as the applicability of digital twin, IoT and blockchain for decision support–centric use.

Inferential statistics computations included a covariance analysis. The covariances were tested using Spearman's rank correlation analyses and performed to explore the respondents' perception on Blockchain-based digital twins' decision support capabilities. Such relationships were of importance for determining the blockchain-based digital twin's role as a decision support tool for asset life cycle management and for cross-comparisons of each individual technological decision support capabilities. The selected statements were the ones

Type of company		Asset management firm		Digitalization consultancy firm		Project management firm	
Role		Manager	8.5%	BIM coordinator	10.9%	Administrator	2.6%
		Operator	9.1%	BIM manager	23.3%	Coordinator	8.0%
		Owner	10.8%	Digitalization specialist	17.6%	Manager	9.4%
Company Size	Large (>250 employees)	18.4%		13.4%		7.8%	
	Medium (50–250 employees)	5.4%		13.4%		6.2%	
	Small (<50 employees)	4.5%		24.8%		6%	
Region	America	3.5%		7.1%		2.4%	
	Asia–Pacific	1.2%		5.9%		1.2%	
	Europe	4.7%		17.6%		5.9%	
	Scandinavia	16.5%		17.6%		10.6%	
	The Middle East	2.4%		3.5%		0%	

Table 2. Distributions in percentages of company roles, sizes, and regions

weighting decision support applicability with industry professionals' perception of the interrelated usability of each technology.

2.2.3 Thematic analysis. The open-ended question responses were analysed thematically using the qualitative data analysis software NVivo© and a grounded theory coding approach. Answers not written in English were translated. All other answers were kept as originally written by the respondents to maintain any sentiments expressed. Themes were then exploratively and inductively identified in NVivo©. High-level hierarchical themes were extracted and coded from the characterization of each open-ended questionnaire question, and the thematic analysis was based on the information within the questionnaire responses. The themes included were:

(1) Emerging technologies' potential to improve asset life cycle management in construction projects.

(2) Solutions for integrating digital twins, legacy asset management systems and blockchains to optimize asset life cycle management.

(3) Achievable levels of interoperability between digital twins, blockchain solutions and smart asset life cycle management systems.

(4) How and what information should be retrievable and assignable to blockchain-based digital twins.

The content of each theme was lastly summarized with a focus on areas of knowledge where there was a consensus among the industry professionals as well as knowledge extractable from statements expressing unique insights.

2.3 Model of framework development

The blockchain-based digital twin model of framework was designed as a process model which was synthesised as a marketable illustration for the paper. The model development was based on the knowledge gained from the literature review, where use cases were identified, and the answers were gathered from the questionnaire, which reported on the technological ecosystems' dynamics and current asset life cycle management practice. One core pillar of the model of framework is represented by the integrability enablers. For which, insights were mainly gained from the thematic NVivo© analysis of the open-ended questions section where industry professionals were asked to freely explain their current and planned digitization initiatives including digital twin, IoT and blockchain projects.

The model of framework highlights the blockchain-based digital twin's use cases, functional interoperability with current practice and technological ecosystems. It also highlights to what extent it can achieve its main objective of providing "live" and information-rich management applications and decision support tools.

3. Theoretical framework

The theoretical framework is built upon findings from the systematic literature review.

3.1 Digital twin

The digital twin concept is generally defined as the digital representation of a tangible asset and its real-time status (Deloitte, 2018; ICE, 2018). Madni *et al.* (2019) have furthermore defined four digital twin levels of sophistication based on the model's ability to provide smart decision support throughout the asset's life cycle.

Generic building information models can be categorized as pre-digital twin models of sophistication level 1. Meanwhile, level 2 digital twins for asset life cycle management are state-of-the art technological ecosystems making use of sensor network, information management and visualization technologies providing asset managers with access to real-time, trustworthy and change-resistant records of asset data (Macchi *et al.*, 2018). The digital twin of sophistication Level 2 has, in particular, one important differentiating attribute. It reassures that information models and data are kept updated in real-time representing the "as-built" building. This in turn enables asset managers to forecast and schedule maintenance based on environmental and operational history. Moreover, insights into asset utilization and tenant behaviour facilitate proactive evidence-based product and service development which generates new opportunities for acquiring and retaining tenants. Adaptive digital twins of sophistication level 3 features machine learning capabilities which provide individualizable decision support and building system regulation. Last but not least, the intelligent digital twin of sophistication level 4 adds the possibility to automatically carry out optimization protocols and immediately regulate IoT connected building systems (Madni *et al.*, 2019; Moin *et al.*, 2019).

It is mainly the improved instant communication attribute that sets high-level digital twins apart from generic models and adds compelling value to asset managers. Even so, the actual derivable value is correlated to the fit between model sophistication levels and the intended as well as realizable usage as cost, time and effort varies for generating the different models (Madni *et al.*, 2019).

3.2 Internet of Things

IoT technologies are represented by interconnected networks of communicating and sensor-data sharing devices (Moin *et al.*, 2019). Sensor devices can detect and respond to conditions and changes in an environment including temperature, humidity, gases, pressure, proximity, acceleration, movement, substance levels and luminance (Koch *et al.*, 2019; Xu *et al.*, 2019). Data from these sensor devices can provide insightful information to asset managers when collected, processed and presented in an intuitive and concise manner which requires an IoT ecosystem including both sensor network and data management solutions (Deloitte, 2018; Ghaffari *et al.*, 2019). Altogether, two major benefits are real-time access to data which enables high-speed reporting and data explosion which makes deep data analytics possible (Ghosh *et al.*, 2020). Among others, three popular technologies for setting up network connections are Wi-Fi (Mistry *et al.*, 2020), bluetooth (Minoli, 2019) and traditional cellular networks, whereas 5G is regarded as the new frontier (Mistry *et al.*, 2020; Lee, 2020).

In the Deloitte (2018) report, it is further highlighted that two fundamental requirements of IoT ecosystems are IT components and connectivity. Both hardware and software for the ecosystem are as of today already widely and affordably available due to recent years' technological advances and mass manufacturing. The IoT net of interconnected devices and sensors is expected to surpass 50bn units during 2020, and the technology has already been applied to all sectors of society (Tahsien *et al.*, 2020) which substantiates its prominence.

3.3 Blockchain

As described by Li *et al.* (2019a, b), the Blockchain technology originates from within the domain of economics and was originally used to record public transactions of the cryptocurrency Bitcoin. The necessity of inducing trust in networks where data are shared was early recognized in the computerization and digitalization research community and has since then developed from timestamping and fork consistency technologies to the Blockchain concept. Haber and Stornetta (1991) argues that a document's validity and correctness can be enhanced with the enablement of timestamping. This further on allows the establishment of trust between stakeholders as information about when a document was created and latest managed makes it useable as evidence of work progression. This is partly something blockchain has adopted as it provides the stakeholders with raw data of when, where and how processes were executed, from beginning to end. A system that could further enable security among stakeholders and their documents is the secure untrusted data repository (SUNDR) network developed by Li *et al.* (2004). SUNDR is based on the fork consistency which guarantees that the user detects any integrity or consistency failures as long as they see each other's file modifications which also the blockchain concept makes use of.

In summary, the blockchain concept is made up of decentralized records of data, both distributed and operated on peer-to-peer networks of computers. Once information, a cryptographic hash of the previous block and a timestamp is uploaded, the blockchain maintains its immutability and reliability, given that all computers have an identical copy of the Blockchain which is checked algorithmically. Authentication is typically achieved through either a proof of work (PoW), proof of stake (PoS) or directed acyclic graph (DAG) consensus mechanism which validates information added to the blocks (Cao *et al.*, 2020; Reyna *et al.*, 2018).

Blockchain's design ensures security and uses cryptography as well as the distributed consensus mechanisms to offer anonymity, persistence, auditability, resilience, and fault tolerance (Erri Pradeep *et al.*, 2019; Li *et al.*, 2019a, b). As a result, the opportunity to endow trust into transactional environments has made the blockchain concept relevant as a carrier of data in segregated asset life cycle management actor networks.

3.4 Smart contracts

Smart Contracts are self-executing pieces of code that execute the terms of a contract upon pre-set obligations being met or conditions occurring (Erri Pradeep *et al.*, 2019; Mathews *et al.*, 2017), whereas the correct execution of the contract can be enforced by the blockchain consensus protocol (Reyna *et al.*, 2018). Osterland and Rose (2020) explored the promising potential of smart contracts when integrated with blockchain technology. With the security gained from a blockchain and the automation of processes enabled by smart contracts, business processes and collaborative peer-to-peer workflow aspects can be automated and correctness ensured, while trust is maintained throughout the actor network. In addition to individual or firm-based contracts, smart contracts can also reliably manage IoT device interactions as well as store and process IoT data (Qian and Papadonikolaki, 2020).

Altogether, when instantiated, smart contracts cannot be manipulated, which adds security to all participants but requires the contracts to be programmed with utmost meticulousness and understanding of the business processes and logic (Singh *et al.*, 2020) due to the irreversibility of the system (Reyna *et al.*, 2018).

The need for third party intermediaries and troublesome interpersonal interactions is moreover reduced when smart contracts are implemented successfully (Tapas *et al.*, 2020; Han *et al.*, 2020). As a result, inter-organizational relationships can be strengthened when the technology is leveraged for unifying the supply chain by shortening the cooperative distance, increasing process transparency and reducing uncertainties (Qian and Papadonikolaki, 2020).

3.5 Use cases

The literature review findings also resulted in, to our knowledge, a comprehensive mapping of use cases for; digital twins, IoT, blockchains and smart contracts for asset life cycle management as summarized in Table 3.

Battisti *et al.* (2019) elaborate that asset managers ought to incorporate the technological ecosystem into their strategic business management planning practice due to gainable market intelligence and possibility to enhance information management. Using IoT while storing the sensor data on a blockchain in a digital twin is found to contribute to improved asset management practice and appears to be applicable to all phases of an asset's life cycle.

Table 3. Technological use-cases for asset lifecycle management

Operation	Approach	Technology	Use cases
Asset Lifecycle Management	Blockchain based Digital Twin	Digital Twin	Dashboard for sensor and device communication. Live data feed of key performance indicators, reporting, task updates, visualizations, simulations and scenario generations. Providing information about the buildings' systems and products including carbon footprint, equipment health, assembly instructions, manufacturer, supply chain and warranty information. Predict and coordinate maintenance work. Real-time decision support for operations, maintenance processes, renovation initiatives and strategic business planning. Benchmarking for new constructions and asset transactions. Assessing goals, certifications, standards, and regulations compliance for quality assurance
		Internet of Things	Sensors monitoring dynamic behaviors, smart user interactions, movement and real-time environmental conditions. As well as space, light, temperature, ventilation utilization and preferences. Tracking water and electricity consumption, in addition to cleanliness and waste levels. Providing the means for gathering sustainability and well-being-centric data. Enabling condition monitoring, damage, and error localization, plus communication with building systems, devices and construction machinery
		Blockchain	Institutionalize trust and facilitate accelerated data transaction times in asset management projects through secure and decentralized logging of building and managerial decision data. Blockchain's storage capabilities include operational, maintenance, access, activity, tenant, utilization, contract, economic, performance, market, project, product, material and installation data
		Smart contract	Automatically regulating building systems featuring smart meter solution for water, energy and grid providers enabling decentralized trading. Predictive planning for maintenance. Defining project teams, deliverables, design packaging, in addition to milestone and completion checking along with follow-up. Cost, budget and time monitoring. Providing smart scheduling solutions; assigning facility managers tasks, registering tenant, work and visitor times, as well as ID verification. Verifying payments and invoices. Contract regulation and compliance together with insurance financial controlling

Fully utilizing the technological ecosystem enhances the transparency, traceability, auditability, immutability of project information. Subsequently, it provides means to achieve modern sustainability goals (Li *et al.*, 2019a, b). The ecosystem supports semi-automated building information modelling, verification, optimisation, simulation, forecasting, status monitoring, diagnosis and regulation. Moreover, it facilitates virtually planning, testing and iteratively (re)configuring on-site machinery, work-in-progress and project participants (Qinglin *et al.*, 2019), thereby providing evidence-based manufacturability and functionality information to decision-makers. The real-time open configuration of the ecosystem empowers collaboration processes for daily facility management, space planning, renovation and new construction initiatives (Zhai *et al.*, 2019). Central for all IoT applications is the monitoring of human-, facility- and environment-related data. Janitorial, utility, mechanical, electrical and groundskeeping maintenance as well as service requests can be scheduled and satisfactorily executed by support of digital twin on-site availability. IoT sensors do also add potential improvements to daily safety and security management as well as for emergency responses (Arslan *et al.*, 2019).

4. Findings and analysis of results

Findings and results are divided into four parts. The first three parts focus on findings from the survey and the fourth on the model of the blockchain-based digital twin framework.

4.1 Descriptive statistics

Descriptive statistics reporting on the mean agreement ratios and standard deviations of questionnaire responses are presented in Table 4. The summarized statistics provide interesting insights as an overview of the asset management industry's perception of the concepts.

The findings indicate a strong sense of awareness regarding the digital transformation of the industry. Many participants were knowledgeable about their companies' digitalization plans ($\bar{x}$ = 3.58) and what BIM level they operate on. The proportion between companies operating above BIM level 2 and those operating below was rather even ($\bar{x}$ = 2.81). The most common digitization initiative was requesting O&M compatible BIM models for new construction and renovation projects ($\bar{x}$ = 3.31). It was correlatively strengthened by the participants' ability to influence digital usage in early stages ($\bar{x}$ = 3.74). The second most common initiative was migrating existing buildings to a digital interface ($\bar{x}$ = 3.06). Digital migration is necessary to standardize asset life cycle management workflows which partly is difficult as of today due to the relatively low percentage of assets with a digital counterpart ($\bar{x}$ = 2.53). Investments in IoT networks have not yet seen similar embracement ($\bar{x}$ = 2.72) nor does most assets already have a sensor network or IoT system installed ($\bar{x}$ = 2.35). At the same time, digital models and IoT systems are not yet widely connected to digital twins ($\bar{x}$ = 1.81). Digital twins were generally recognized to be important for effectivizing current processes and its usability as real-time decision support ($\bar{x}$ = 3.88) was central. The overall perception of IoT networks was positive. Identified use cases for IoT including communication with building systems and devices along with machinery condition, damage, error localization and reduced equipment downtime were perceived to be highly relevant ($\bar{x}$ = 4.27). The industry professionals were slightly more estranged to the Blockchain use cases whereas most, besides transactional ($\bar{x}$ = 4.08) and work tendering ($\bar{x}$ = 3.73) uses, scored lower than the other technological use cases. Regarding blockchain's data storing capabilities, the respondents were most optimistic towards storing building information and managerial decision data ($\bar{x}$ = 3.48), followed by storing IoT data ($\bar{x}$ = 3.40).

Table 4. Descriptive statistics analysis

	Questionnaire statement	Statistic mean	Std Deviation
Asset management	We approach asset management from a life cycle perspective	3.55	1.26
	We have a clear digitalization plan	3.58	1.15
	We are operating on at least BIM level 2	2.81	1.53
	We can influence BIM and digital usage and requirements during early planning and design phases	3.74	1.31
	We require O&M compatible BIM models for new constructions and renovation projects	3.31	1.37
	A large percentage of our properties have a digital model counterpart	2.53	1.39
	A large percentage of our properties have a sensor network or IoT system	2.35	1.27
	A large percentage of our digital models and IoT systems are connected in a digital twin	1.81	1.20
	We migrate our existing non-digitized buildings to a digital interface	3.06	1.43
	We invest in IoT networks and sensor systems for new construction and renovation projects	2.72	1.35
	We train our facility managers to use digital solutions	3.18	1.26
Digital twin	Digital twins are good for providing live data feeds of key performance indicators, visualizations, simulations, and scenario generations applications	3.71	1.33
	A digital twin provides real-time decision support for operations, maintenance processes, renovation initiatives and strategic business planning	3.88	1.19
	Digital twins are useable as dashboards for sensor and device communication	3.67	1.16
	Without a digital twin it is time consuming to gather information about buildings' systems and products including carbon footprint, equipment health, manufacturer and supply chain information	3.74	1.21
	Digital twin solutions are integrable with our current practice	3.19	1.38
Internet of things	Tenant interactions are important to monitor for optimizing buildings' performance and sustainability as well as reducing costs	4.04	0.94
	Insight into light, temperature and ventilation preferences can help increase tenant satisfaction and wellbeing	4.45	0.70
	IoT is useable for communicating with building system and devices as well as monitoring machinery condition, damage, error localization and reduced equipment downtime	4.27	0.85
	IoT data supports well informed decision-making resulting in optimization opportunities for occupant, staff,and management experiences	4.11	0.96
	IoT solutions are interoperable with our digital ecosystem	3.09	1.33
Blockchain	Blockchain technology is useable as a secure and cost-efficient decentralized information storage hub facilitating accelerated data transaction times	3.36	1.16
	Blockchain ledgers are useable for storing IoT device and sensor data for inclusion in shared transactions with tamper-resistant records	3.40	1.10
	Blockchain technology could efficiently log building information and managerial decision data	3.48	1.13
	Assigning facility managers tasks through self-executing Smart Contracts can improve scheduling and reduce response times	3.73	1.13
	Automatically verifying payments and invoices could save administrative costs	4.08	0.97
	Blockchain solutions synergize well with our data management systems	2.87	1.33

The asset management industry has seemingly had a slow technological adoption pace. However, as knowledge and incentives increase, because of maturing acceptance of digitization benefits, the rate of technological embracement accelerates. Yet there are significant standard deviations within the sample which indicates that there are large progression fluctuations between industry actors. The standard deviation of operating on BIM level 2 or higher is large ($\sigma = 1.53$). This indicates that the industry is yet highly fragmented with firms' digitization initiatives still being far from aligned. A basic prerequisite for working with digital twins is having digital model counterparts. Despite that, the initiatives for migrating existing non-digitized buildings to a digital interface ($\sigma = 1.43$) and the percentages of properties with digital model counterparts ($\sigma = 1.39$) varies significantly too.

4.2 Thematic analysis

The thematic analysis of the open-ended questionnaire responses using NVivo© is presented in Table 5.

Analysing the first theme, emerging technologies' potential to improve asset life cycle management in construction projects results in a couple of interesting key findings. Significant agreement between the industry professionals and literature findings are found for the technologies' potential to optimize asset management processes, provide critical project information, visualizations, timeline and capital expenditure estimations, instruct when/how/why asset products need to be replaced and how to recycle, reuse or refurbish assets. There are also alignments for the technologies' expected benefits such as the enablement of preventative maintenance, improved administrative efficiency, error and risk reduction, enhanced decision-making, agile feedback loops, information re-use as well as improved management practice quality.

The second theme is solution requirements. Organizational prerequisites include early planning inclusion, clearly motivated ROI and solving communication challenges between information silos. Technical prerequisites include gathering information on standardized data collection platforms, where semantic data can be searched for and used, as well as common standards and data formats, non-proprietary systems, uniform interfaces, modular platform design and data level storage including momentary, temporary and permanent storage. A solution where the requirements are being met is expected to function with and to be accessible by different software brands' systems.

The third theme focuses on the achievable levels of interoperability. The findings showcased a rather wide range of beliefs depending on previous experiences. It ranged from a stand-alone solution to a fully integrated and centralized decision support tool. Statements within the theme included human factors as the need for user-friendliness was key. Primarily, non-tech-savvy users should be able to use the platform without difficulties.

Lastly, the analysis of insights for the fourth theme, how and what information should be retrievable and assignable to the blockchain, highlighted the need for information to be logged on several separate and scalable ledgers (i.e. unique ones for sensor, transaction and asset management data). The ledgers must also have the ability to be merged into one blockchain, and the Blockchain would need different consensus mechanisms to suit the type of data to be stored. Information about the building components can suggestively be carried by digital tags included in BIM objects and traceable on-site with QR codes.

4.3 Correlation analyses

Central for blockchain-based digital twins is its decision support capabilities. The correlations between the perceived capabilities of the ecosystem as a collective with each individual technology's capabilities thus helps establish what technologies are fundamental

Table 5. Thematic analysis of the open-ended questionnaire responses

Coded themes	Thematic answer summary analysis
Emerging technologies' potential to improve asset life cycle management in construction projects	Optimize asset management processes, provide critical project information, visualizations, timeline and capital expenditure estimations, instruct when/how/why asset products need to be replaced and how to recycle, reuse or refurbish assets. This includes, team coordination and work scheduling, project progress follow-up, streamlined communication, collection of experiences and structured information to be transferred to future projects or to be used throughout the life cycle. Trust, immutability and cybersecurity can be reassured in data streams and blockchain records, resulting in the enablement of preventative maintenance, improved administrative efficiency, error and risk reduction, enhanced decision-making, agile feedback loops, information re-use as well as improved management practice quality
Solution requirements for integrating digital twins, legacy asset management systems and blockchains to optimize asset life cycle management	The blockchain-based digital twin must be included in contracts for renovation and new construction projects as early on as during the initial planning phase. The strategic value and expected ROI of blockchain-based digital twins must be clear for all involved stakeholders. The value must be motivated on both a firm and national level. Regarding the technical solution, digital information must be gathered in one uniform interface: a central, standardized data collection platform, where semantic data can be searched for and used. Common standards, data formats and non-proprietary systems are thus necessary for integrability and a modular design of the platform makes it accessible and useable by different software brands' systems. Interoperability with AI, machine learning tools and user-involvement methods for aggregating quantitative data from the digital twin with qualitative data from user research is also important. Communication challenges between information silos must be solved, and data level storage should include momentary, temporary, and permanent storage. This reduces the risk of blockchain ledgers becoming too heavy for use when many blocks eventually have been logged. "Light access" solutions for mobile devices are necessary to allow users to access the blockchain data without having to download or update the whole ledger
Achievable levels of interoperability between Digital Twins, Blockchain solutions and smart asset life cycle management systems	The desired lowest level includes the displaying of current conditions as well as a service request tendering system. It can be semi-autonomous if managed by a skilled asset manager and if open data standards and protocols have been clearly stated. Simplifying behind-the-scenes tasks are necessary so that asset managers who are not tech-savvy can use systems. A more advanced level includes the complete removal of financial and administrative friction and the automation of payments, incentive systems, work process

(*continued*)

Coded themes	Thematic answer summary analysis
	initiation and project progression management. This is the result of a fully interoperable blockchain-based digital twin solution where trust is embedded into the stakeholder networks, adding probity and reliability
How and what information should be retrievable and assignable to blockchain based Digital Twins	Information must be logged on several separate and scalable ledgers (i.e. unique ones for sensor, contract, transaction, building information and asset management data) with the ability to be merged into one blockchain. The use of a DAG consensus mechanisms in the IoT ledgers is advisable due to its ability to merge different ledger branches into one blockchain, satisfactory performances in generating new blocks quickly, as well as manageable confirmation delay and confirmation failure probability. The block size of DAG is however much smaller compared to PoS, meaning that for example building information is more suitable to be stored through a PoS consensus mechanism. PoW is comparably not a very suitable consensus mechanism as the high computing difficulty results in meaningless energy consumption. Blockchain solutions can further on be amplified using QR codes and BIM objects. All components should have a digital tag for tracking it through its manufacturing, transportation, installation, use and decommissioning. Material passport and life cycle position information should also be assignable and retrievable from the blockchain. Cross-platform integration with manufacturers' databases would be ideal for access to warranty, designated use, maintenance notifications and additional manufacturer data

for manifesting the decision support functionality. This, in turn, helps shed a light onto the importance of the technologies' integrability enablement from an industry professional's usability perspective. The correlation calculations of respondents' perception on blockchain-based digital twins' decision support capabilities is visualized in Table 6.

4.4 Model of framework

The model of the blockchain-based digital twin framework is illustrated in Figure 1.

Two of the five dimensional pillars are independent of any other pillar, including: physical assets which functions without support from any of the technologies and blockchains which serves other purposes without any integration with any of the other technologies. However, a few dimensions are completely reliant on others, in particular, digital twin implementation which requires both a physical asset and IoT networks for it to provide a useable service. In any other case its usability becomes entirely hypothetical. Also, the blockchain-based digital twin dimension is fully reliant on all other pillars for its strategic planning, multifunctional on-field support and decision support applicability to be realized. As there is strong support from both literature and industry professionals for these functionalities, the model of the framework seeks to set up a conceptual ecosystem structure where a holistic approach to implementing the system is taken. The ecosystem is thus not supposed to be integrated through stepwise implementation but instead as a comprehensive transformative project. The connected boxes visualize what technological platforms must merge in between the dimensional pillars and their interconnected cross-platform reliance for the purpose of developing a blockchain-based digital twin ecosystem.

An asset management solution developer may start at the utmost left pillar by investigating what systems are available for physical asset and then take systematic steps to the right making sure there are interoperable solutions for each interconnected platform along the way when progressing towards the blockchain-based digital twin. Integrable IoT sensor, smart device and building automation system platforms are needed in between the physical asset and IoT dimensions. These must in turn be interoperable with digital building maintenance systems and AIM platforms which merge the IoT and digital twin dimensions. This in turn connects with the digital twin platform which with integration with blockchain-based decentralized smart contract and data hubs completes the blockchain-based digital twin ecosystem.

Below the dimensional pillars are three bars: functionality, interoperability and integrability enablers, which visually describe where within the ecosystem these dimensions come into play or are necessary to consider when merging the technological platforms. As shown, the interoperability and the integrability enablers are first and foremost representable for a solution which functionality is a planning, on-field support and decision-making tool. Interoperability between the three individual technologies as well as the blockchain-based digital twin platform is crucial, and to achieve this, each integrability enabler must conform to each individual technology and to the technologies as a collective.

5. Discussions

In accordance with the aim, this study explored technological use-cases, the applicability, interoperability and interoperability of a blockchain-based digital twin for asset life cycle management, and a model of framework was developed for positioning the digital twin within a broader context of current management practice and technological availability. There was significant overlap between the literature findings and the professionals' experienced and perceived usability and applicability of digital twins, IoT networks and blockchain storage hubs as synthesized in the thematic analysis.

Table 6. Correlation analysis of respondents' perception on blockchain-based digital twins decision support capabilities

		Spearman's rank correlation coefficient matrix			
		Digital twins for KPIs and simulations**	Digital twin as decision support***	IoT data for decision-making****	Blockchain technology for logging info*****
Spearman's Rho (ρ)	Digital twins for KPIs and simulations**	1.000	0.877*	0.623*	0.572*
	Digital twin as decision support***	0.877*	1.000	0.593*	0.591*
	IoT data for decision-making****	0.623*	0.593*	1.000	0.548*
	Blockchain technology for logging info*****	0.572*	0.591*	0.548*	1.000

Note(s): $N = 85$
All correlations had a 2-tailed Sig. < 0.000
*Correlation is significant at the 0.01 level (2-tailed)
**Digital twins provide live data feeds of KPIs, visualizations, simulations, and scenario generations applications
***A digital twin provides real-time decision support for operations, maintenance processes, renovation initiatives and strategic business planning
****IoT data supports well informed decision-making, resulting in optimization opportunities for occupant, staff and management experiences
*****Blockchain technology could efficiently log building information and manageri'al decision data

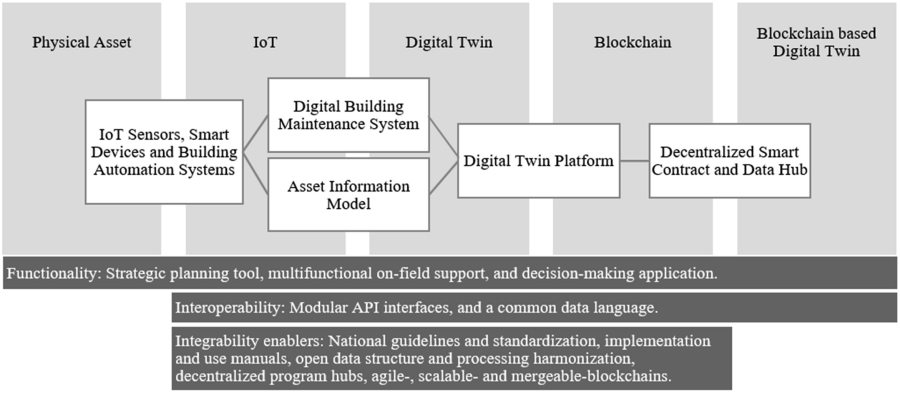

Figure 1. Blockchain based Digital Twin model of framework

5.1 Decision support capabilities

The blockchain-based digital twin's decision support capabilities and the interoperability of the digital twin, IoT and blockchain technologies were two frequently encountered themes. The strongest correlation between digital twin's decision support capabilities and the technologies' individual capabilities were with digital twins usability for providing live data feeds of KPIs, visualizations, simulations and scenario generation ($\rho = 0.877$). The second strongest correlation was with the use of IoT data for supporting well-informed decision-making ($\rho = 0.593$). The weakest correlation was with blockchains' usability for information logging ($\rho = 0.591$). At the same time, the digital twin was perceived to be the most integrable with current practice and digital ecosystems ($\bar{x} = 3.19$). IoT was perceived to be the second most integrable technology ($\bar{x} = 3.09$), and the synergization of blockchain with current data management systems had the lowest agreement ratio mean ($\bar{x} = 2.87$).

The novelty of Blockchain technology within the asset management sector could partly explain why any decision support–centric correlations with blockchains' usability for information logging was low. Big data cloud storage and processing is yet another prominent alternative for logging asset life cycle management information (Koch *et al.*, 2019). Due to the subsidies the blockchain's interchangeability is low and is a probable cause for a lower usability and reliance perception. Furthermore, as discussed by Newman *et al.* (2020), the focus on building information modelling implementation consumes much focus of industry professionals and other technologies within Industry 4.0 are as a result subsided.

The weakest correlation, with a Spearman's rho coefficient of 0.591, was with the statement exploring IoT data supporting well- informed decision-making. This aligns with Arowoiya *et al.* (2020) findings of yet rather low understanding of the IoT concept within the real estate industry. Further training and education could help with the adoption of the technology and the perceived usability of its decision support capabilities.

5.2 Integrability enablement

Solution requirements for a blockchain-based digital twin include establishing guidelines and standardizing planning and management practice processes (Koch *et al.*, 2019). Industry professionals stated that failing to properly define strategic values could dilute the purpose of the digital twin and make it both costly and wasteful. As clients and the market demand are large drivers, the requirements for O&M must be established during initial project tendering. Derivable is the suggestion of (re)developing the BIM manual concept to prepare it for O&M-centric blockchain-based digital twin use, whereas much like BIM goals, project standards, roles, suggested work practice, responsibilities and delivery requirements in relation to relevant digital twin levels of sophistication should be stated. With firm and national level guidelines for cross-disciplinary standardization, communicated through manuals prepared for asset life cycle management, the effect of error-prone digital twins could diminish, and thus a greater user experience of the technological ecosystem would transpire.

Blockchain-based digital twins must be embedded into the technological ecosystem in a cost neutral manner and with an interoperable modular interface. Currently the technologies are vertically integrated by device vendors or through in-house pilot projects as siloed, standalone solutions. This resonates with the findings of Koch *et al.* (2019) where FM systems having non-uniform interfaces make information exchanges and data processing inefficient. Digital twins, IoT and Blockchain integration is thus difficult. Heterogenous modularity is, as of today and to our knowledge, not offered for a holistic technological solution as integrability is often locked behind data monetization or specific vendor partnerships. The proposed ecosystem ought to be built on a non-proprietary platform with modular, user-friendly, API-based interfaces between the digital twin, IoT, blockchain as well as various building, product and customer management solutions. One key integrability enabler is open data structure and processing harmonization, which partly can be achieved by a common linked data language and multiple agile, scalable and mergeable blockchain ledgers for logging different types of data and for enabling temporal storage. This could also make the data accessible and useable by different software brands' solutions, and it would allow customers to customize their blockchain-based digital twin solutions. Such customizations could include smart city management solutions as argued by Dewan and Singh (2020).

Koch *et al.* (2019) findings further support the integrability enabler of information standardization as they argue that it improves the interoperability of digitized infrastructure. However, one area where standardization seems to be counterproductive is for the blockchain consensus mechanisms and data storage methods. Asset life cycle management data varies significantly. Building information could greatly benefit from a blockchain solution featuring big data distributed database and file-sharing characteristics. On the other hand, in accordance with Reyna *et al.* (2018) findings, IoT integration with the blockchain-based digital twins require consensus solutions to filter, compress and normalize high volumes of data to ensure that only useable and size-efficient data are embedded into the ecosystem. Lastly, separable blockchains help combat errors arising when the networks increase in scale and collaboration of the different system areas must work seamlessly as individually flawed areas can more easily be targeted for troubleshooting.

5.3 Practical implications

The blockchain-based digital twin provides a unified collaboration solution for industry professionals to use as decision and process support for a wide range of asset life cycle management activities as identified in the survey findings and discussed by other researchers, including, Macchi *et al.* (2018), Arowoiya *et al.* (2020), Hunhevicz and Hall (2020), and Qian and Papadonikolaki (2020). Both strategic decisions making such as portfolio and business management and on-field asset management such as scheduled as well as daily maintenance practice are supported.

Practically, work tasks will be distributed by smart contracts, and asset managers will receive notifications of daily goals. Guidance is received through access to the information-rich digital twins which are in real-time updated by the physical asset's IoT network. All activities are transparently logged on the ecosystems' sets of blockchains which ensure trustworthy project data logging. This way the correct products are maintained by the right person at the most opportune time. Implications of its use include better informed decision- making, improved service quality, resource optimization and supply chain defragmentation. Reducing costs by reducing upfront efforts leads to more efficient project execution which in turn supports the allocation of more funds to sustainable and well-being-centric products and practice.

6. Conclusions and recommendations

The results strongly support the conclusion that there is significant potential to holistically approach current digitization initiatives with blockchain-based digital twins, as well as the positioning of the concept as both a strategic tool and a multifunctional on-field support application. User-friendliness, accessibility as well as user- and implementation manuals are necessary prerequisites for successful implementation. Integrability enablers include progression towards BIM level 3, decentralized program hubs, modular interfaces and a set of mergeable and scalable blockchains.

The technological use-case mapping significantly contributes to the knowledge domain of digitized asset life cycle management as of today and the projected foreseeable future. Nonetheless, the risk of the mapping not being complete must be acknowledged as no structured and holistic study of all pilot projects nor innovation labs was made. It should also be recognized that the early state of technological adaptation within the real estate industry naturally make the use cases more noncommittal as the technologies evolve and matures.

Increasing the survey sample, geographical distribution and response rate would improve the study's reliability. This paper does also not investigate the economics of implementing the proposed technological ecosystem. Neither does it cover the necessary restructuring of organizations, new business models, resource allocation, implementation plans, nor competence requirements of facility managers for working with blockchain-based digital twins. The digital twin and blockchain technologies are still relatively vaguely tested for asset management applications, and there are unexplored technical limitations and organizational drivers hindering its implementation.

Future research recommendations include having think-tank discussions with industry professionals which would contribute with insights into managerial and socio-economic implications. Case-studies of innovation labs developing digital win, IoT, blockchain and smart contract solutions for asset life cycle management could help complement and strengthen the evidence for the use case mapping. Organizational prerequisites ought to be further researched to assess the feasibility of industry-wide adaptation. Further on, mapping available technologies, linked data ontology solutions and their usability alignment with the blockchain-based digital twin would provide a foundation for developing an actual blockchain-based digital twin ecosystem for pilot testing.

References

Ammari, K.E. and Hammad, A. (2014), "Collaborative BIM-based markerless mixed reality framework for facilities maintenance", *Computing in Civil and Building Engineering (2014)*, pp. 657-664.

Arowoiya, V.A., Oke, A.E., Aigbavboa, C.O. and Aliu, J. (2020), "An appraisal of the adoption internet of Things (IoT) elements for sustainable construction", *Journal of Engineering, Design and Technology*, Vol. 18 No. 5, pp. 1193-1208, doi: 10.1108/JEDT-10-2019-0270.

Arslan, M., Cruz, C. and Ginhac, D. (2019), "Understanding occupant behaviors in dynamic environments using OBiDE framework", *Building and Environment*, Vol. 166, doi: 10.1016/j.buildenv.2019.106412.

Battisti, E., Shams, S.M.R., Sakka, G. and Miglietta, N. (2019), "Big data and risk management in business processes: implications for corporate real estate", *Business Process Management Journal*, Vol. 26 No. 5, pp. 1141-1155, doi: 10.1108/BPMJ-03-2019-0125.

Bew, M. and Richards, M. (2008), "Bew-Richards BIM maturity model", *BuildingSMART Construct IT Autumn Members Meeting*, Brighton.

BIM Task Group (2011), "A report for the government construction client group - building information modelling (BIM) working party strategy paper", *Department of Business, Innovation and Skills*, available at: https://www.cdbb.cam.ac.uk/system/files/documents/BISBIMstrategyReport.pdf (accessed 12 September 2020).

Cao, B., Zhang, Z., Feng, D., Zhang, S., Zhang, L., Peng, M. and Li, Y. (2020), Performance analysis and comparison of PoW, PoS and DAG based blockchains, *Digital Communications and Networks*. doi: 10.1016/j.dcan.2019.12.001, in press, corrected proof.

Cheng, J.C.P., Chen, W., Tan, Y. and Wang, M. (2016), "A BIM-based decision support system framework for predictive maintenance management of building facilities", *16th International Conference on Computing in Civil and Building Engineering (ICCCBE2016)*, 6–8 July 2016, Osaka, available at: http://hdl.handle.net/1783.1/77685 (accessed 12 September 2020).

Davidson, J., Fowler, J., Pantazis, C., Sannino, M., Walker, J., Sheikhkhoshkar, M. and Rahimian, F.P. (2019), "Integration of VR with BIM to facilitate real-time creation of bill of quantities during the design phase: a proof of concept study", *Frontiers of Engineering Management*, Vol. 7, pp. 396-403, doi: 10.1007/s42524-019-0039-y.

Deloitte (2018), "IoT powered by Blockchain: how Blockchains facilitate the application of digital twins in IoT", Blockchain Institute Issue 05/2018, available at: https://www2.deloitte.com/content/dam/Deloitte/de/Documents/Innovation/IoT-powered-by-Blockchain-Deloitte.pdf (accessed 12 September 2020).

Dewan, S. and Singh, L. (2020), "Use of blockchain in designing smart city", *Smart and Sustainable Built Environment*, Vol. ahead-of-print No. ahead-of-print, doi: 10.1108/SASBE-06-2019-0078.

Ding, Z., Liu, S., Liao, L. and Zhang, L. (2019), "A digital construction framework integrating building information modeling and reverse engineering technologies for renovation projects", *Automation in Construction*, Vol. 102, pp. 45-58, doi: 10.1016/j.autcon.2019.02.012.

Erri Pradeep, A.S., Yi, T.W. and Amor, R. (2019), "Leveraging blockchain technology in a BIM workflow: a literature review", *International Conference on Smart Infrastructure and Construction 2019, ICSIC*, ICE Publishing, pp. 371-380, doi: 10.1680/icsic.64669.371.

Ghaffari, K., Lagzian, M., Kazemi, M. and Malekzadeh, G. (2019), "A comprehensive framework for Internet of Things development: a grounded theory study of requirements", *Journal of Enterprise Information Management*, Vol. 33 No. 1, pp. 23-50, doi: 10.1108/JEIM-02-2019-0060.

Ghosh, A., Edwards, D.J. and Hosseini, M.R. (2020), "Patterns and trends in Internet of Things (IoT) research: future applications in the construction industry", *Engineering Construction and Architectural Management*, Vol. ahead-of-print No. ahead-of-print, doi: 10.1108/ECAM-04-2020-0271.

Goulding, J.S. and Rahimian, F.P. (2012), "Industry preparedness: advanced learning paradigms for exploitation", *Construction Innovation and Process Improvement*, Blackwell Publishing, Wiley and Sons, Oxford, pp. 409-433, doi: 10.1002/9781118280294.ch18.

Haber, S. and Stornetta, W.S. (1991), "How to time-stamp a digital document", *Journal of Cryptology*, Vol. 3, pp. 99-111, doi: 10.1007/BF00196791.

Han, D., Zhang, C., Ping, J. and Yan, Z. (2020), "Smart contracts architecture for decentralized energy trading and management based on blockchain", *Energy*, Vol. 199, doi: 10.1016/j.energy.2020.117417.

Heaton, J., Parlikad, A.K. and Schooling, J. (2019), "Design and development of BIM models to support operations and maintenance", *Computers in Industry*, Vol. 111, pp. 172-186, doi: 10.1016/j.compind.2019.08.001.

Helo, P. and Hao, Y. (2019), "Blockchains in operations and supply chains: a model and reference implementation", *Computers and Industrial Engineering*, Vol. 136, pp. 242-251, doi: 10.1016/j.cie.2019.07.023.

Hunhevicz, J.J. and Hall, M.D. (2020), "Do you need a blockchain in construction? Use case categories and decision framework for DLT design options", *Advanced Engineering Informatics*, Vol. 45, doi: 10.1016/j.aei.2020.101094.

ICE (2018), *Blockchain Technology in the Construction Industry: Digital Transformation for High Productivity*, Institution of Civil Engineers, London. doi: 10.13140/RG.2.2.14164.45443.

Kang, T.W., Park, S.H. and Hong, C.H. (2016), "BIM/GIS-based data integration framework for facility management", *GEO Processing 2016: The Eighth International Conference on Advanced Geographic Information Systems, Applications, and Services*, 2016, available at: https://www.semanticscholar.org/paper/BIM%2FGIS-based-Data-Integration-Framework-for-Kang-Park/13823330f49e94b4582d45c1d5676ce1d0d46c0a#citing-papers (accessed 12 September 2020).

Karan, E.P. and Irizary, J. (2014), "Developing a spatial data framework for facility management supply chains", in Castro-Lacouture, D., Irizarry, J. and Ashuri, B. (Eds), *Construction Research Congress 2014*, ASCE, Reston, VA, pp. 2355-2364, doi: 10.1061/9780784413517.239.

Koch, C., Hansen, G.K. and Jacobsen, K. (2019), "Missed opportunities: two case studies of digitalization of FM in hospitals", *Facilities*, Vol. 37 Nos 7/8, pp. 381-394, doi: 10.1108/F-01-2018-0014.

Lee, H., Kang, D., Ryu, J., Won, D., Kim, H. and Lee, Y. (2020), "A three-factor anonymous user authentication scheme for Internet of Things environments", *Journal of Information Security and Applications*, Vol. 52, doi: 10.1016/j.jisa.2020.102494.

Li, J., KrohnMazières, M.D. and Shasha, D. (2004), "Secure untrusted data repository (SUNDR)", *Proceedings of the 6th Symposium on Operating Systems Design and Implementation*, December 2004, OSDI' 04, San Francisco, CA.

Li, J., Greenwood, D. and Kassem, M. (2019a), "Blockchain in the built environment and construction industry: a systematic review, conceptual models and practical use cases", *Automation in Construction*, Vol. 102, pp. 288-307, doi: 10.1016/j.autcon.2019.02.005.

Li, Y., Kubicki, S., Guerriero, A. and Rezgui, Y. (2019b), "Review of building energy performance certification schemes towards future improvement", *Renewable and Sustainable Energy Reviews*, Vol. 113, doi: 10.1016/j.rser.2019.109244.

Lou, E., Mohdrahim, F., Zainon, N., Sulaiman, S. and Zulkifli, N. (2019), "Sustainability-led design: feasibility of incorporating whole-life cycle energy assessment into BIM for refurbishment projects", *Journal of Building Engineering*, Vol. 10, pp. 1-16, doi: 10.1016/j.jobe.2019.01.027.

Love, E.D.P. and Matthews, J. (2019), "The 'how' of benefits management for digital technology: from engineering to asset management", *Automation in Construction*, Vol. 107, doi: 10.1016/j.autcon.2019.102930.

Lydon, G.P., Caranovic, S., Hischier, I. and Schlueter, A. (2019), "Coupled simulation of thermally active building systems to support a digital twin", *Energy and Buildings*, Vol. 202, doi: 10.1016/j.enbuild.2019.07.015.

Macchi, M., Roda, I., Negri, E. and Fumagalli, L. (2018), "Exploring the role of digital twin for asset lifecycle management", *IFAC-PapersOnLine*, Vol. 51 No. 11, pp. 790-795, doi: 10.1016/j.ifacol.2018.08.415.

Madni, A.M., Madni, C.C. and Lucero, S.D. (2019), "Leveraging digital twin technology in model-based systems engineering", *Systems*, Vol. 7 No. 1, p. 7, doi: 10.3390/systems7010007.

Manavalan, E. and Jayakrishna, K. (2018), "A review of Internet of Things (IoT) embedded sustainable supply chain for industry 4.0 requirements", *Computers and Industrial Engineering*, Vol. 127, pp. 925-953, doi: 10.1016/j.cie.2018.11.030.

Mathews, M., Robles, D. and Bowe, B. (2017), "BIM+Blockchain: a solution to the trust problem in collaboration?", CITA BIM Gathering November 23rd-24th 2017, Technological University of Dublin, Dublin, Ireland. doi: 10.21427/D73N5K.

McArthur, J.J. (2015), "A building information management (BIM) framework and supporting case study for existing building operations, maintenance and sustainability", *Procedia Engineering*, Vol. 118 No. 1, pp. 1104-1111, doi: 10.1016/j.proeng.2015.08.450.

Mehrbod, S., Staub-French, S., Mahyar, N. and Tory, M. (2019), "Characterizing interactions with BIM tools and artifacts in building design coordination meetings", *Automation in Construction*, Vol. 98, pp. 195-213, doi: 10.1016/j.autcon.2018.10.025.

Minoli, D. (2019), "Positioning of blockchain mechanisms in IOT-powered smart home systems: a gateway-based approach", *Internet of Things*, Vol. 1, doi: 10.1016/j.iot.2019.100147.

Mistry, I., Tanwar, S., Tyagi, S. and Kumar, N. (2020), "Blockchain for 5G-enabled IoT for industrial automation: a systematic review, solutions, and challenges", *Mechanical Systems and Signal Processing*, Vol. 135, doi: 10.1016/j.ymssp.2019.106382.

Moher, D., Liberati, A., Tetzlaff, J. and Altman, D.G. and The PRISMA Group (2009), "Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement", *PLoS Medicine*, Vol. 6 No. 7, doi: 10.1371/journal.pmed.1000097.

Moin, S., Karim, A., Safdar, Z., Safdar, K., Ahmed, E. and Imran, M. (2019), "Securing IoTs in distributed blockchain: analysis, requirements and open issues", *Future Generation Computer Systems*, Vol. 100, pp. 325-343, doi: 10.1016/j.future.2019.05.023.

Motawa, I. and Almarshad, A. (2013), "A knowledge-based BIM system for building maintenance", *Automation in Construction*, Vol. 29, pp. 173-182, doi: 10.1016/j.autcon.2012.09.008.

Muller, M., Esmanioto, F., Huber, N., Rocha, L.E. and Canciglieri, O.J. (2019), "A systematic literature review of interoperability in the green building information modeling lifecycle", *Journal of Cleaner Production*, Vol. 223, doi: 10.1016/j.jclepro.2019.03.114.

Negri, E., Davari Ardakani, H., Cattaneo, L., Singh, J., Macchi, M. and Lee, J. (2019), "A digital twin-based scheduling framework including equipment health index and genetic algorithms", *IFAC-PapersOnLine*, Vol. 52 No. 10, pp. 43-48, doi: 10.1016/j.ifacol.2019.10.024.

Newman, C., Edwards, D., Martek, I., Lai, J., Thwala, W.D. and Rillie, I. (2020), "Industry 4.0 deployment in the construction industry: a bibliometric literature review and UK-based case study", *Smart and Sustainable Built Environment*, Vol. ahead-of-print No. ahead-of-print, doi: 10.1108/SASBE-02-2020-0016.

Nysveen, H., Pedersen, P. and Skard, S. (2020), "Ecosystem adoption of practices over time (EAPT): toward an alternative view of contemporary technology adoption", *Journal of Business Research*, Vol. 116, pp. 542-551, doi: 10.1016/j.jbusres.2020.01.014.

Osterland, T. and Rose, T. (2020), "Model checking smart contracts for Ethereum", *Pervasive and Mobile Computing*, Vol. 63, doi: 10.1016/j.pmcj.2020.101129.

O'Sullivan, D.T.J., Keane, M.M., Kelliher, D. and Hitchcock, R.J. (2004), "Improving building operation by tracking performance metrics throughout the building lifecycle (BLC)", *Energy and Buildings*, Vol. 36 No. 11, pp. 1075-1090, doi: 10.1016/j.enbuild.2004.03.003.

Oti, A.H., Kurul, E., Cheung, F. and Tah, J.H.M. (2016), "A framework for the utilization of building management system data in building information models for building design and operation", *Automation in Construction*, Vol. 72, pp. 195-210, doi: 10.1016/j.autcon.2016.08.043.

Parkinson, T., Parkinson, A. and de Dear, R. (2019), "Continuous IEQ monitoring system: context and development", *Building and Environment*, Vol. 149, pp. 15-25, doi: 10.1016/j.buildenv.2018.12.010.

Qian, X.A. and Papadonikolaki, E. (2020), "Shifting trust in construction supply chains through blockchain technology", *Engineering Construction and Architectural Management*, Vol. ahead-of-print No. ahead-of-print, doi: 10.1108/ECAM-12-2019-0676.

Qinglin, Q., Fei, T., Tianliang, H., Nabil, A., Ang, L., Yongli, W., Lihui, W. and Andrew, N. (2019), "Enabling technologies and tools for digital twin", *Journal of Manufacturing Systems*. doi: 10.1016/j.jmsy.2019.10.001, in press, corrected proof.

Rahimian, F.P., Ibrahim, R., Wirza, R., Abdullah, M.T. and B Hj Jaafar, M.S. (2011), "Mediating cognitive transformation with VR 3d sketching during conceptual architectural design process", *International Journal of Architectural Research*, Vol. 5 No. 1, pp. 99-113, doi: 10.26687/archnet-ijar.v5i1.221.

Rashid, K., Louis, J. and Fiawoyife, K. (2019), "Wireless electric appliance control for smart buildings using indoor location tracking and BIM-based virtual environments", *Automation in Construction*, Vol. 101, pp. 48-58, doi: 10.1016/j.autcon.2019.01.005.

Reyna, A., Martín, C., Chen, J., Soler, E. and Díaz, M. (2018), "On blockchain and its integration with IoT. Challenges and opportunities", *Future Generation Computer Systems*, Vol. 88, pp. 173-190, doi: 10.1016/j.future.2018.05.046.

Shojaei, A., Wang, J. and Fenner, A. (2019), "Exploring the feasibility of blockchain technology as an infrastructure for improving built asset sustainability", *Built Environment Project and Asset Management*, Vol. 10 No. 2, pp. 184-199, doi: 10.1108/BEPAM-11-2018-0142.

Singh, A., Parizi, M.R., Qi, Z., Kim-Kwang Raymond, C. and Dehghantanha, A. (2020), "Blockchain smart contracts formalization: approaches and challenges to address vulnerabilities", *Computers and Security*, Vol. 88, doi: 10.1016/j.cose.2019.101654.

Tahsien, M.S., Karimipour, H. and Spachos, P. (2020), "Machine learning based solutions for security of internet if things (IoT): a survey", *Journal of Network and Computer Applications*, Vol. 161, doi: 10.1016/j.jnca.2020.102630.

Tapas, N., Longo, F., Merlino, G. and Puliafito, A. (2020), "Experimenting with smart contracts for access control and delegation in IoT", *Future Generation Computer Systems*, Vol. 111, pp. 324-338, doi: 10.1016/j.future.2020.04.020.

Tchana de Tchana, Y., Ducellier, G. and Sébastien, R. (2019), "Designing a unique Digital Twin for linear infrastructures lifecycle management", *Procedia CIRP*, Vol. 84, pp. 545-549, doi: 10.1016/j.procir.2019.04.176.

Wetzel, E.M. and Thabet, W.Y. (2015), "The use of a BIM-based framework to support safe facility management processes", *Automation in Construction*, Vol. 60, pp. 12-24, doi: 10.1016/j.autcon.2015.09.004.

Wong, J.K.W., Li, H., Wang, H., Huang, T., Luo, E. and Li, V. (2013), "Toward low-carbon construction processes: the visualisation of predicted emission via virtual prototyping technology", *Automation in Construction*, Vol. 33, pp. 72-78, doi: 10.1016/j.autcon.2012.09.014.

Wong, J.K.W., Ge, J. and He, X.S. (2018), "Digitisation in facilities management: a literature review and future research directions", *Automation in Construction*, Vol. 92, pp. 312-326, doi: 10.1016/j.autcon.2018.04.006.

Xu, J., Lu, W., Xue, F. and Chen, K. (2019), "'Cognitive facility management': definition, system architecture, and example scenario", *Automation in Construction*, Vol. 107, doi: 10.1016/j.autcon.2019.102922.

You, Z. and Wu, C. (2019), "A framework for data-driven informatization of the construction company", *Advanced Engineering Informatics*, Vol. 39, pp. 269-277, doi: 10.1016/j.aei.2019.02.002.

Zhai, Y., Chen, K., Zhou, X.J., Cao, J., Lyu, Z., Jin, X., Shen, Q.P.G., Lu, W. and Huang, Q.G. (2019), "An Internet of Things-enabled BIM platform for modular integrated construction: a case study in Hong Kong", *Advanced Engineering Informatics*, Vol. 42, doi: 10.1016/j.aei.2019.100997.

Zibin, Z., Shaoan, X., Hong-Ning, D., Weili, C., Xiangping, C., Jian, W. and Muhammad, I. (2019), "An overview on smart contracts: challenges, advances and platforms", *Future Generation Computer Systems*, Vol. 105, pp. 475-491, doi: 10.1016/j.future.2019.12.019.

Further reading

Chen, K., Lu, W.S., Peng, Y., Rowlinson, S. and Huang, G.Q. (2015), "Bridging BIM and building: from a literature review to an integrated conceptual framework", *International Journal of Project Management*, Vol. 33 No. 6, pp. 1405-1416, doi: 10.1016/j.ijproman.2015.03.006.

Messner, M., Anumba, C., Dubler, C., Goodman, S., Kasprzak, C., Kreider, R., Leicht, R., Saluja, C. and Zikic, N. (2019), "Design authoring: BIM use", *BIM Project Execution Planning Guide – Version*

2.2, Computer integrated Construction Research Program, Penn State College of Engineering, Pennsylvania, PA, available at: https://www.bim.psu.edu/design_authoring/ (accessed 5 March 2020).

Appendix

The Appendix is available online for this article.

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