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Review

Digital Twins and Blockchain technologies for building lifecycle management

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ABSTRACT

This paper reviews the potential applications of Digital Twins (DT) and Blockchain (BC) technologies throughout the building lifecycle phases by conducting a double-stranded systematic review of papers on the possible use of DT and BC. The results revealed the increasing interest in DT and BC and their potential use in all building lifecycle phases; however, studies focused mainly on the construction phase. The findings also revealed unique features of DT and BC, potentially supporting the proposal for their collaborative implementation to enhance building lifecycle management. This review's findings positioned the argument for more research on integrating DT and BC to augment building lifecycle management and the need to explore their relevance or role when transitioning from construction to post-construction. This paper elucidates readers on the potential role of DT and BC while developing a built asset and suggests directions for future research.

1. Introduction

The Architectural, Engineering, Construction, and Facility Management (AEC-FM) industry involves complex activities due to the variety and volumes of entities involved, the duration of a project, and the amount of relevant data generated [98]. Therefore, this creates breeding grounds for lost information, untracked implementation, and most critically unfulfilled client requirements, especially during the different phases of a building's lifecycle.

Van Groesen and Pauwels [132] highlight that these complexities result from the AEC-FM industry's fragmented nature, with many geographically dispersed stakeholders and different layers of contractors and subcontractors involved in a construction project working together towards a common goal. Therefore, critical activities during a built asset's lifecycle can often be skipped, rushed due to time constraints, or even ignored entirely despite the enormous criticality it plays for acceptance by the client and support for the smooth occupancy of the built asset.

There has been an increasing trend in adopting digital technologies in various industries, especially with the advent of Industry 4.0, to overcome industry complexities. However, the AEC-FM industry has slowly adopted, used, or applied emerging digital technologies [92]. Current studies have shown that applying digital technologies in the AEC-FM industry increases productivity and improves collaboration, quality, and efficiency, contributing to project success [5]. Some emerging technologies include Building Information Modelling (BIM), Digital Twins (DT), Distributed Ledger Technologies (DLT) or Blockchain (BC), 3D printing, Internet of Things (IoT), Artificial Intelligence (AI), Augmented or Virtual Reality [155,156]. Within the AEC-FM industry, especially under the concepts of Construction 4.0, efforts are being made to adopt such emerging technologies and tap into their advanced capabilities throughout the different lifecycle phases [95].

Currently, BIM, a digital illustration of what will be constructed or manufactured [66], is the common tool or process in the AEC-FM industry used to ensure efficient collaboration and communication [94,124]. Despite the multi-level capabilities of BIM, it remains limited to implementation within the digital realm without in-feed of real-time information for a close to "as-built" or "up-to-current" state of the built asset being actualised in the physical form [79]. However, even with this challenge addressed, issues arise from fragmentation with information sharing, communication inconsistencies, and participant delays. These complications can result in accountability issues, particularly during the transition from construction to post-construction, when supporting the operational performance of a building during its utilisation stages.

DT surpasses BIM by providing more "up-to-current" modelling capabilities and can offer AI-driven "what-if" simulations to identify

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solutions for issues like schedule delays and budget overruns, empowering stakeholders to make informed decisions proactively [66]. IoT sensors coupled with DTs can also make BIM a living instrument, automatically updating 'as-built' BIM [29]. Several studies have highlighted that creating and managing DT is a journey relevant to the entire project lifecycle [138]. Nonetheless, these studies have also underscored the significance of ensuring security, reliability, and improved collaboration concerning the generated data [46].

Consequently, BC provides potentially unified standards and protocols for information sharing with a decentralised peer-to-peer framework and addresses information security and privacy based on the cryptographic mechanism [32,123]. Hence, BC could be a suitable technology to overcome or manage the challenges of DT regarding its security, reliability and enhancing trust and transparency throughout a built asset's lifecycle [62]. BC can also be a channel to address failures in communication among project participants and minimise information loss during a building's lifecycle [33].

With the AEC-FM industry's increasing research focus on the potential of emerging technologies, significant literature reviews have been carried out on DT or BC studies. Within DT literature, reviews have focused on DT applications for building energy efficiency [7], DT applications in the construction industry [95], the drivers for DT adoption [96], and DT fault detection in buildings [48]. Similarly, BC reviews have focused on BC's potential and limitations [91], the risks and opportunities of BC applications in the construction industry [19], and the anticipated benefits and challenges of applying BC in AEC [13]. Despite the growing number of reviews, little attention has been paid to highlighting the complementary potential of DT and BC in the AEC-FM literature. To the best of the authors' knowledge, only one similar review study has been conducted by Sadri et al. [111], who examined the potential of enabling technologies in integrating BC and DT in the smart built environment. Nevertheless, their study lacks a comprehensive review of the potential applicability of BC and DT during the different stages of a building's life cycle. Although increasing studies on DT and BC indicate that their relevance encompasses all the phases of the lifecycle of a building, this study delves into the potential utilisation and the rationale for the integration of DT and BC at the different phases of a building's lifecycle to help identify the trends and possible application areas. Hence this paper presents a systematic literature review to tackle the following:

1. State-of-art DT applications within the context of preconstruction, construction, and post-construction lifecycle phases.
2. State-of-art of BC applications within preconstruction, construction, and post-construction lifecycle phases.
3. Identify the complementary features of DT and BC necessary for enhanced building lifecycle management.
4. Highlight research gaps identified for both DT and BC applications within the context of building lifecycle phases.

The significance of this study lies in its contribution to the frontier of knowledge on the relevance of emerging technologies in the Architecture, Engineering, Construction and Facility Management (AEC-FM) industry. It supports nudging further research directions for actualising the desired state of digital construction, especially incorporating digital technologies in building lifecycle management. The remainder of the article is structured as follows: Section 2 gives a background overview of the core constructs of this study. Section 3 outlines the systematic literature review process adopted for this study. Section 4 presents the results of the literature review. Section 5 discusses the literature findings, highlighting the gaps and the study's limitations. Section 6 highlights the recommendations emerging from this study, and Section 7 finally summarises and concludes the study.

2. Overview of building lifecycle management

This study's perspective is on a building's lifecycle, which can be divided into preconstruction, construction, and post-construction phases [99], where stakeholders perform value-generating activities at each phase according to defined requirements. The preconstruction phase includes project initiation, planning, design etc., executed before construction. The construction phase includes works carried out to monitor and achieve project outputs, whilst the post-construction phase consists of activities undertaken after construction works are complete, including monitoring building operations, maintenance activities etc.

The management of each phase is generally done independently due to the different activities and stakeholders involved; however, participants are confronted with a lot of data across the different phases, which is crucial in understanding the performance of building systems and components and informing decision-making [82]. Therefore, effective resource management is imperative for successful project management and critical for organising and exploiting relevant information to support decision-making processes throughout the project lifecycle.

The AEC-FM industry still lacks a comprehensive way to manage, capture, exchange, use, and control data and information throughout an asset's lifecycle [50], especially during the transition from construction to post-construction, which usually comprises building handover activities, considered critical and increasingly required for every building due to the recent incorporation of complex building systems [107]. Building handover activities, including commissioning and post-occupancy evaluation, are faced with the issues of manual data handling, inconsistencies in the representation, format and meaning of the data generated [82], which can lead to errors and data loss, fragmented and inaccurate information, and poor decision-making. This results in critical issues during post-construction activities, which costs time and money [83]. Therefore, there is a need to focus on the efficient management and continuity of relevant information to enhance effective management and decision-making, especially when the building is in use.

One possible way to ensure efficient decision-making and effective management throughout a building's lifecycle and contribute to addressing transition issues is to explore the relevance of BC and DT throughout the different lifecycle phases. Consequently, effective 'real-time' monitoring, secured data management and enhanced collaboration are needed to improve the management of a built asset.

3. Research methodology

A systematic literature review was selected as the most suitable method to effectively determine the current state of research in a focal field of study. This approach enables structured gathering, evaluation, and synthesis of relevant literature to provide valuable insights and identify potential areas for further research [38]. This study's systematic literature review focuses explicitly on works related to the potential use of DT and BC for the preconstruction, construction, and post-construction phases of a building. By focusing on a systematic literature review of DT and BC technologies for the AEC-FM industry, the study identifies relevant evidence within the extant literature [37]. Two strands of the review were conducted, namely, DT and BC, ensuring both strands adhered to systematic literature review techniques and principles of conduct like replicability, retrievability, summarisation, synthesis and transparency.

To improve the process quality and mitigate against the risk of bias, a comprehensive search was performed across two databases, namely Scopus and Web of Science Core Collection, based on recommendations from the Peer Review of Electronic Search Strategies (PRESS) [84]. These databases were chosen because they are the top two ranked databases for trustworthy and peer-reviewed research, which indexes most academic publications worldwide [54]. This search strategy of utilising at least two literature sources was considered apt since not all referencing papers may be cited by a single database [37].

3.1. Identification of potential papers

Search terms were tested for appropriateness in finding relevant literature by conducting the preliminary search in both Scopus and Web of Science Core Collection; a comprehensive search was then completed in December 2022, using the keywords and Boolean operators presented in Table 1.

Search filters applied included publication date (2018 onwards), literature type (journal article, conference papers), and language type (English). The filters were chosen based on pragmatic decisions made in consultation with review team members (authors), considering emerging results during the preliminary test searches and following recommendations by Denyer and Tranfield [22]. The year 2018 was selected as the specific timeframe for this study because the primary literature relevant to the research was published during that period. The study relied on journal articles and conference papers mainly due to the focus on primary studies. Lastly, the review team's language proficiency influenced the language constraints. Retrieved results from each strand were aggregated, and any duplicate papers were removed before advancing into the screening stage. As a result, papers that progressed to the screening stage comprised 514 papers out of 1588 retrieved for the DT strand and 381 papers out of 2211 retrieved for the BC strand.

3.2. Screening of relevant papers

Papers that progressed into the screening stage were scanned for relevance to the subject matter by reading their titles and abstracts; then, their full texts were sought and thoroughly read to assess their eligibility using the criteria outlined in Table 2 to progress papers for content extraction.

Effectively papers that advanced into the 'included' stage for further analysis comprised 48 papers out of 514 papers for the DT strand and 64 papers out of 381 papers for the BC strand, as presented in Fig. 1.

3.3. Included papers for relevant information extraction

A merger of papers that passed the eligibility assessments of both DT and BC strands of screening had no duplicates. Thus, the contents of 112 papers were subjected to relevant information extraction into three main building lifecycle categories. A detailed thematic coding on descriptions of DT and BC applications within identified building lifecycle categories was conducted using NVivo, by the eligibility mentioned above criteria in Table 2. Similar thematic areas were merged to form the three building lifecycle categories whose contents were quantified to conduct content analysis to determine significant themes, trends and other metrics (quantitative and qualitative) in answering the study's research goals [1]. Accordingly, the building lifecycle categories comprised preconstruction (27 papers), construction (70 papers), and post-construction (27 papers). Based on Page et al.'s [97] recommendations on evidence synthesis, the PRISMA flow diagram was used to capture process flows for both Fig. 1 DT and BC strands, as presented in Fig. 1.

Table 1
Search Strategy per Strand.

Strand	Keywords	Boolean	Additional Keywords
Digital Twin (DT)	("digital twin*" OR "virtual counterpart*" OR "digital replica" OR "virtual twin*" OR "digital twin concept" OR "building twin*" OR "digital building twin")	AND	("construction" OR "construction industry" OR "built environment" OR "building industry")
Blockchain (BC)	("distributed ledger*" OR "block chain*" OR "blockchain*" OR "distributed ledger technology")	AND	("construction" OR "construction industry" OR "built environment" OR "building industry")

Table 2
Content Inclusion and Exclusion Criteria.

Inclusion	Exclusion
• Studies that report primary studies on DT and BC applications	• Studies that aggregate or mainly synthesise existing knowledge as summaries, like reviews
• DT and BC applications for construction within building lifecycle phases	• DT and BC discussions that are for exemplary purposes and demonstrate no application
• Studies within the preconstruction, construction, and post-construction building life cycle phases	• DT and BC integrations were discussed but not clearly identifiable to a building lifecycle phase.

Additionally, the features of included papers were assessed based on the representative publication years. Finally, the findings were used to arrive at the state-of-art and gaps in the literature by cross-comparison of DT and BC strands.

4. Results and analysis

The systematic review results of the 112 papers identified and selected are presented and described in this section according to quantitative breakdowns and qualitative summaries of DT and BC applications within each of the three main building life cycle phases (preconstruction, construction, and post-construction) considered.

4.1. Overview of studies on Digital Twins for building lifecycle phases

Results from the DT strand of the systematic literature review process to answer this study's aim about state-of-the-art and potential gaps are presented hereafter. Forty-eight papers emerged from the DT strand and were utilised within this section to derive the presented results. Publications included within the DT strand span over a timeline from 2019 to 2022 and are growing significantly, as revealed in their distribution: 2019 (1 paper); 2020 (9 papers); 2021 (22 papers); and 2022 (16 papers). Also, the main document types were Journal Articles (27 papers) and Conference Papers (21 papers). Fig. 2 and Fig. 3, respectively, present trends on papers grouped into building lifecycle phases based on publication years and type. Additionally, a cumulative count of papers based on publication years and document types demonstrates the aggregated growth in DT research patterns.

The observed trends in Fig. 2 and Fig. 3 suggest that within conference and journal papers, DT applications in the post-construction phase were an initial focus; however, attention to construction phase applications has dominated the research timeframe, whilst preconstruction applications seem to be a recent emerging focus.

4.2. Digital twins for building lifecycle phases

Studies on DT in AEC-FM literature are growing, making the concept of DT gain some awareness in the industry [4]. Results from the DT strand were clustered into themes based mainly on a built asset's lifecycle phases (preconstruction, construction, and post-construction) to determine the value that can be retrieved from the potential use of DTs for the different phases. See Fig. 4 for a summary of DT application areas within a building's lifecycle found in the literature.

Although studies have highlighted DT as a promising concept that can benefit different processes within the AEC-FM industry, it is still farfetched and in the early stages of development and implementation in academia and industry [114]. According to Opoku et al. [95], adopting DT would inherently deliver improved lifecycle costs, reduced carbon emissions, and resilient built assets in an ever-increasing environmentally aware society. However, some of the roadblocks highlighted in

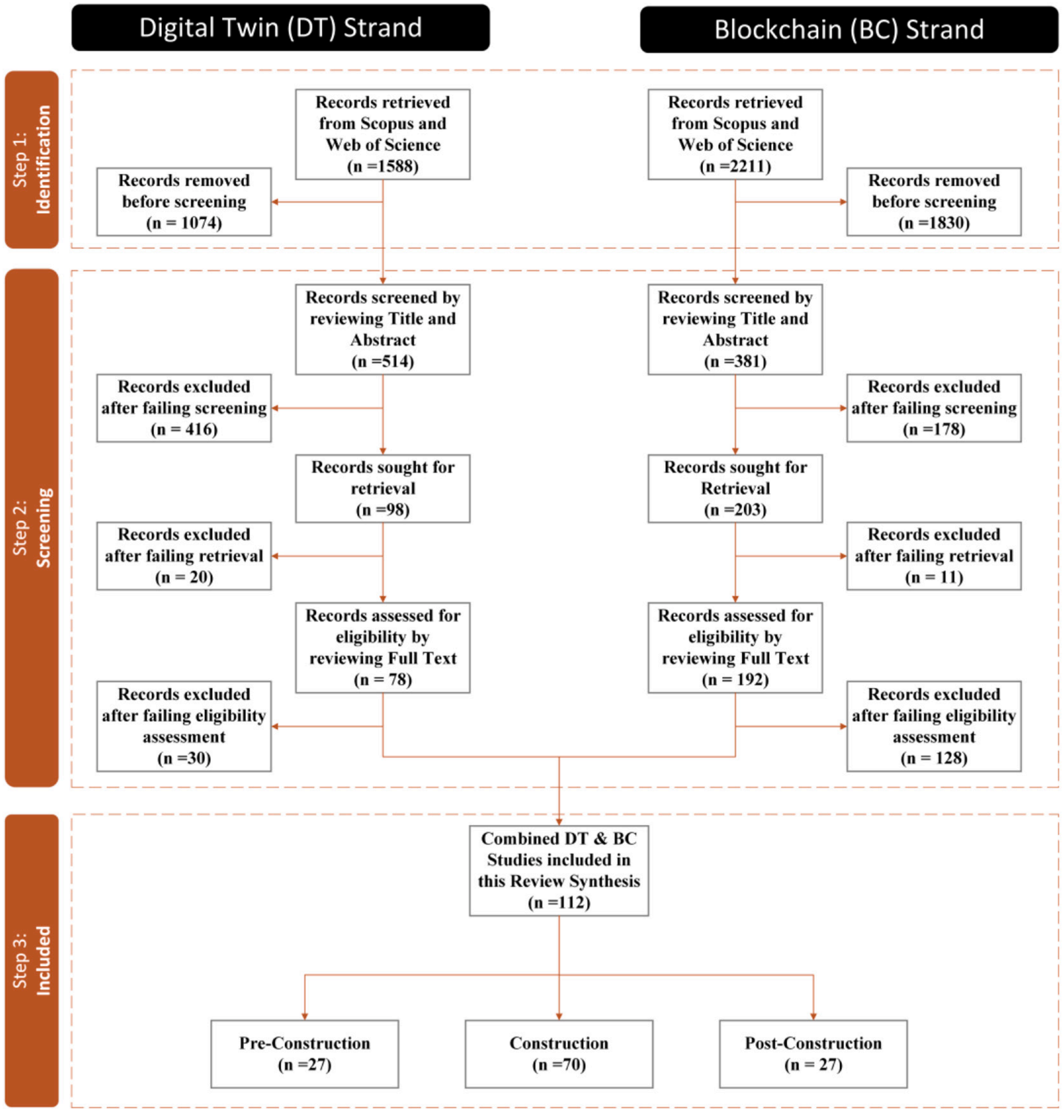

Fig. 1. PRISMA Flow Diagram for Digital Twin and Blockchain Strands.

literature that threatens the implementation of DT in the built environment include a lack of consensus on DT concepts in practice, difficulty in exhaustively evaluating DTs' varied capabilities, and struggle experienced by practitioners in clear understanding of the required changes in an organisation's processes to realise and sustain value generated from the DT [2]. See Table 3 for the classification summary of literature included in the DT strand according to constructed themes.

4.2.1. DT for preconstruction phase

Studies on integrating DT for preconstruction activities focused on planning and design decision-making, tendering evaluation, sustainability assessment, and environmental monitoring. DT has the potential to help extract data, make efficient designs and allocate resources as part of the preconstruction process [64].

In an era focused on green buildings and sustainability in the built environment, DT has the potential to support sustainability goals during preconstruction activities. Tagliabue et al. [122] proposed a framework that incorporated a DT-based Internet of Things (IoT)-enabled dynamic approach to allow for real-time sustainability assessment from a user's perspective during design. The system suggested by the study can contribute to reliably supporting the control and monitoring of the built environment towards a green and sustainable environment. Similarly, Shen et al. [116], in their quest to address the challenges encountered in achieving net zero carbon emissions in a built environment, developed a conceptual framework of DT to enable the capturing and monitoring of real-time conditions of buildings for enhanced decision-making on carbon emissions and environmental issues throughout a built asset's lifecycle. Meschini et al. [85] further adopted an approach to integrate DT prototypes and artificial intelligence to automate and evaluate tendering procedures, optimise performance and contribute to sustainability.

4.2.2. DT for construction phase

In the construction phase of a building's life cycle, potential applications of DT have focused on construction progress monitoring, construction safety, construction site disaster preparedness, construction management, and construction waste management.

Studies have highlighted that integrating DT with other technologies can support collaborative work in creating, analysing, visualising, and managing construction progress data and reports. This assertion is supported by Alizadehsalehi and Yitmen [141], who presented a framework that integrates BIM, DT, and extended reality technologies in developing an automated construction progress monitoring system. Similarly, Li et al. [67] proposed an accurate construction progress monitoring framework using DTs with sensor data to update 4D BIM automatically and reliably in determining construction progress and reflecting the reality of a project.

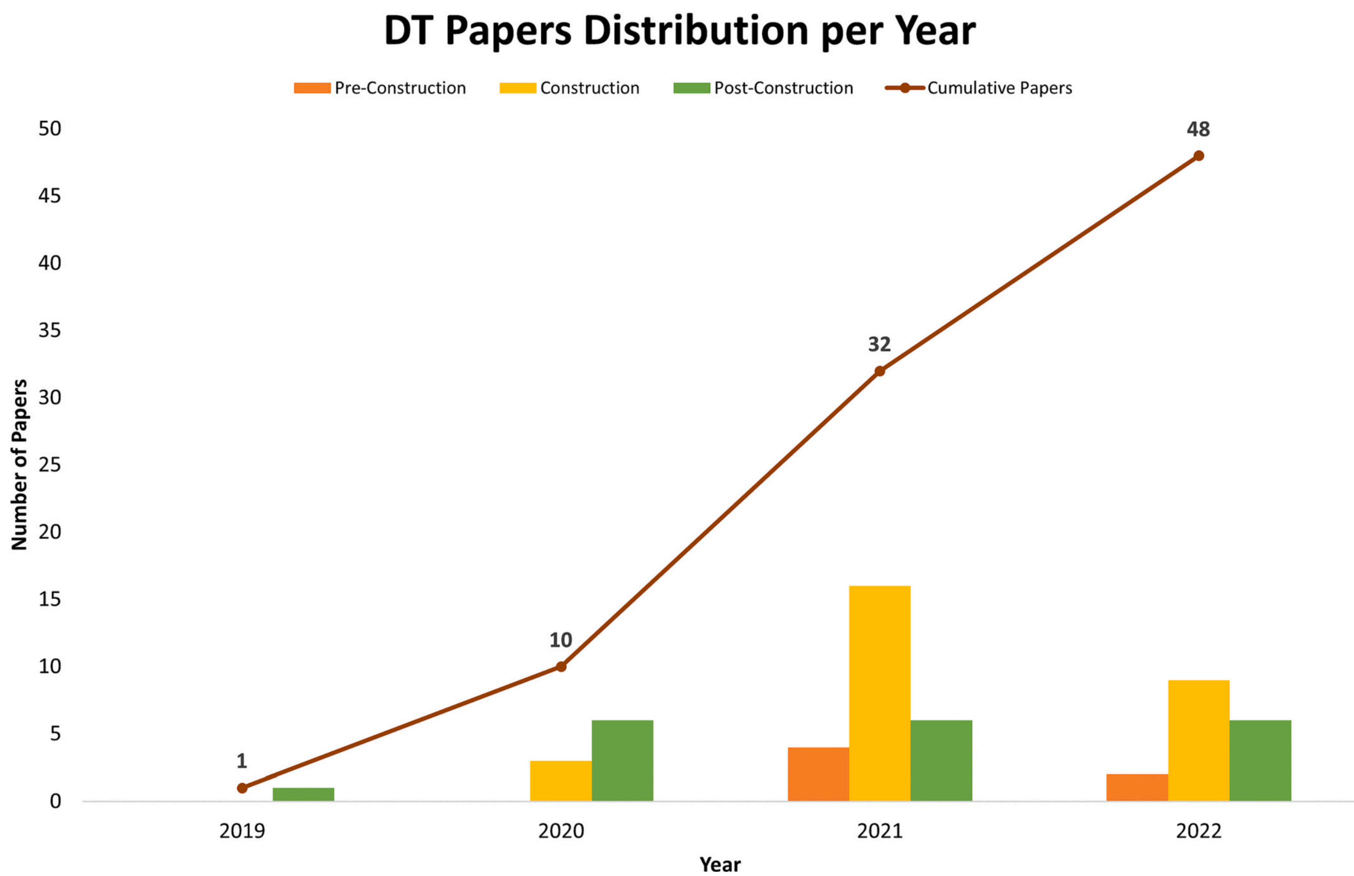

Fig. 2. Digital Twin Papers' Trend based on Publication Years.

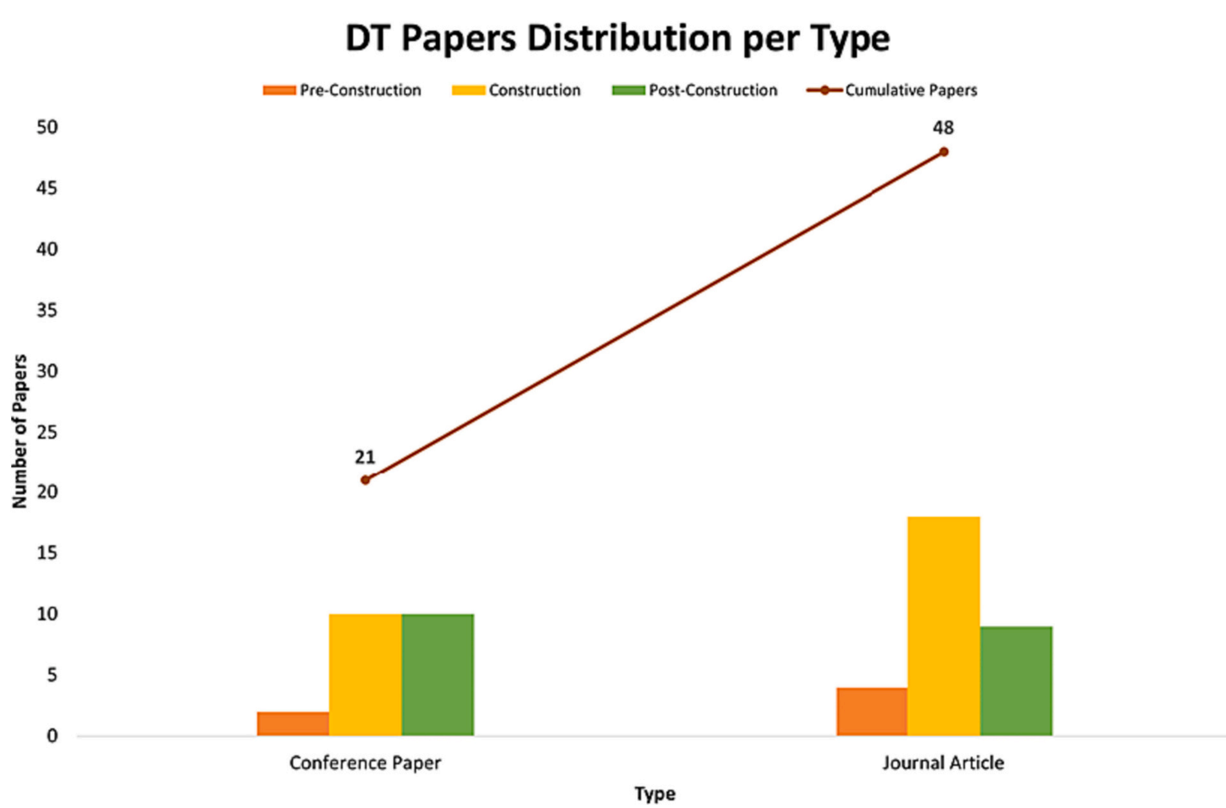

Fig. 3. Digital Twin Papers' Trend Based on Document Types.

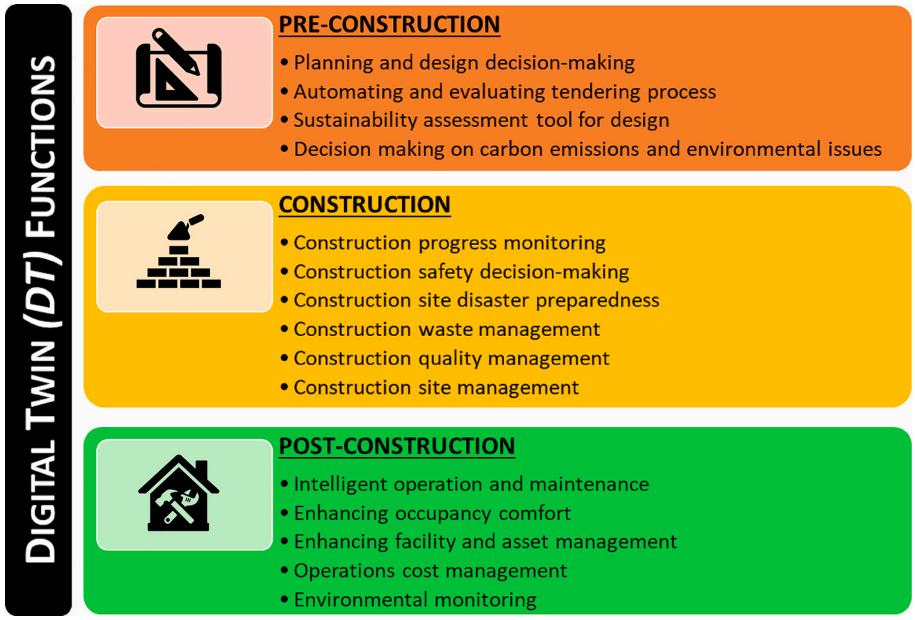

Fig. 4. Areas of Digital Twin Applications in AEC-FM Literature.

Table 3
Overview of Digital Twin Application Themes from AEC-FM Literature.

Building Lifecycle Phase	No of Studies	DT LITERATURE Authors/References
DT for Preconstruction	6	([64], [85], [102], [122], [143], [153])
DT for Construction	29	[4,12,16,44,51,56–58,61,63,64,67,71,76,77,86,98,102,106,109,110,121,127,129,135,137,142,143,152]
DT for Post-Construction	16	([14], [24], [34], [39], [45], [49], [73], [75], [87], [122], [133], [134], [139], [145], [146], [147])

For construction management, Sun and Liu [121] proposed a DT-BIM hybrid model to aid in decision-making, progress updates, dispatching resources and identifying the shortage of resources. DTs can assist in quality evaluation during construction by providing insights into geometric quality, checking completeness and accuracy, and helping guide adjustments of building elements [130]. Jiang [56] applied DT technology to the simulation of the construction process and construction management, featuring construction site management, safety during construction, and quality and operation management. The study explored the effectiveness of DT construction management via simulation research, which proved that the efficiency of construction management could be enhanced via the timely formulation of a reliable construction management plan. Lin and Wu [136] introduced an integrated framework for twinning and mining a construction project's collaborative network, which entailed collecting collaborative data related to the construction project's on-site inspection. The proposed framework allows managers to evaluate collaborators' performance, detect critical actors and understand how people work collaboratively to complete construction tasks.

The emergence of DT platforms for construction safety has also become necessary for timely, intelligent safety decision-making via deriving safety information from value-creating raw data [127]. Chronopoulos et al. [16] proposed a safety framework which involved the interaction with a DT platform to aid in the reduction of potential hazards on construction sites. As part of the framework, sensory information was continuously integrated with the DT in a construction environment to identify hazard areas, predict accidents and their impacts, and notify the workers of these hazards. From a disaster preparedness perspective, Kamari and Ham [57] proposed a novel method based on DT and risk assessment to aid in hurricane preparedness by systematically identifying potential wind-borne debris based on job site characteristics. The proposed method contributes to making risk-informed decisions and implementing proactive measures towards hurricane preparedness.

4.2.3. DT for post-construction phase

DT literature retrieved for post-construction was mainly focused on the use of DT for real-time interactions, predictability, enhanced decision-making during operation and maintenance activities, facility, and asset management. According to Rao et al. [103], DT has the potential to aid facility managers in testing and planning maintenance activities and monitoring and predicting building conditions. Y. Liu et al. [75] further posit that DT has the potential to provide owners and property managers with real-time operational costs of green buildings, providing a reasonable basis for effective decision-making.

In work undertaken by Y. Zhao et al. [147], a framework involving the integration of a machine learning algorithm with a DT for building operations was proposed. According to the studies, the distinct characteristics of DT's virtual interaction and real-time response provide a platform to achieve intelligent operation and maintenance management via data-driven intelligent prediction and diagnosing the status of a building's operation and maintenance. Using a data-driven approach, Vivi et al. [133] presented a system architecture for developing DTs at the building level to provide a platform for humans to relate to buildings via intelligent and sustainable channels. The research was further examined using real-world development to establish the capability of DT in predicting, tracking, and improving asset maintenance. Wang et al. [134] focused on developing a DT-based built environment sensing and monitoring which incorporates data required to support real-time environmental monitoring and communicates actionable insights for informed decisions while managing building facilities.

Lin et al. [73] proposed a live DT model that included the development of the dynamic behaviour of a building's HVAC system via sensor data to facilitate the efficient analysis of a constructed environment. The authors posit that the use of DT for HVAC systems in the built environment aids in the significant reduction of cost of energy usage whilst maintaining occupant comfort. Findings from the framework proposed by Hosamo et al. [49] demonstrated that the efficiency of an HVAC system could be enhanced via automatic fault detection of air handling units. The proposed approach utilises a DT predictive maintenance framework to diagnose and detect faults and predict the conditions of building components. The research highlighted the possibility of formulating and implementing maintenance strategies to overcome the limitations in building facilities' maintenance management systems.

4.3. Overview of studies on Blockchain for building lifecycle phases

Results from the BC strand of the systematic literature review process to answer this study's aim on the state-of-the-art and potential gaps are presented hereafter. Sixty-four papers emerged from the BC strand and were utilised within this section to derive the presented results. Publications included within the BC strand span over a timeline from 2018 to 2023 and are growing significantly, as revealed in their distribution: 2018 (1 paper); 2019 (9 papers); 2020 (13 papers); 2021 (20 papers); 2022 (18 papers); and 2023 (3 papers). Also, the main document types were Journal Articles (43 papers) and Conference Papers (21 papers). Fig. 5 and Fig. 6, respectively, present trends on papers grouped into building lifecycle phases based on publication years and type. Additionally, a cumulative count of papers based on publication years and document types demonstrates the aggregated research growth patterns.

The observed trends in Fig. 5 and Fig. 6 suggest that within conference and journal papers, BC applications in the preconstruction phase were an initial focus; however, traction for construction phase applications has dominated the research timeframe, whilst post-construction applications seem to be a rapidly growing focus.

4.4. Blockchain for building lifecycle phases

Although BC is regarded as the technology likely to have a significant impact [32], due to its potential to solve some problems experienced in the industry, it is still relatively new to industry players. BC studies retrieved were also clustered into their potential use for building lifecycle phases. Research on BC in AEC-FM literature has indicated its potential to enhance construction efficiency, reduce issues with fragmentation and communication and lessen paper-based operational activities [59]. See Fig. 7 for a summary of BC application areas within a building's lifecycle found in the literature.

BC's development in the AEC-FM industry is still hampered by some challenges [59]. According to Kumar Singh et al. [65], some challenges can be deduced from stakeholders' unawareness of BC, stakeholders' unwillingness to adopt and rely on new technology and the discomfort of sharing business information in a distributed environment. On the other hand, Sharma and Kumar [115] suggest that adopting BC, like any new technology, may depend on stakeholders' willingness to take a risk and their preparedness to invest in this unproven concept even though it has great potential. See Table 4 for the classification summary of literature included in the BC strand according to constructed themes.

4.4.1. BC for preconstruction phase

Research on BC for preconstruction activities mainly focused on using BC for the planning process, sustainable building design, design collaboration, optimisation of the design process, and tendering evaluation. Studies of BC implementation are increasing, mainly due to its potential to enhance transparency in a collaborative environment [28].

Berawi et al. [6] suggested a BIM-based BC model to support

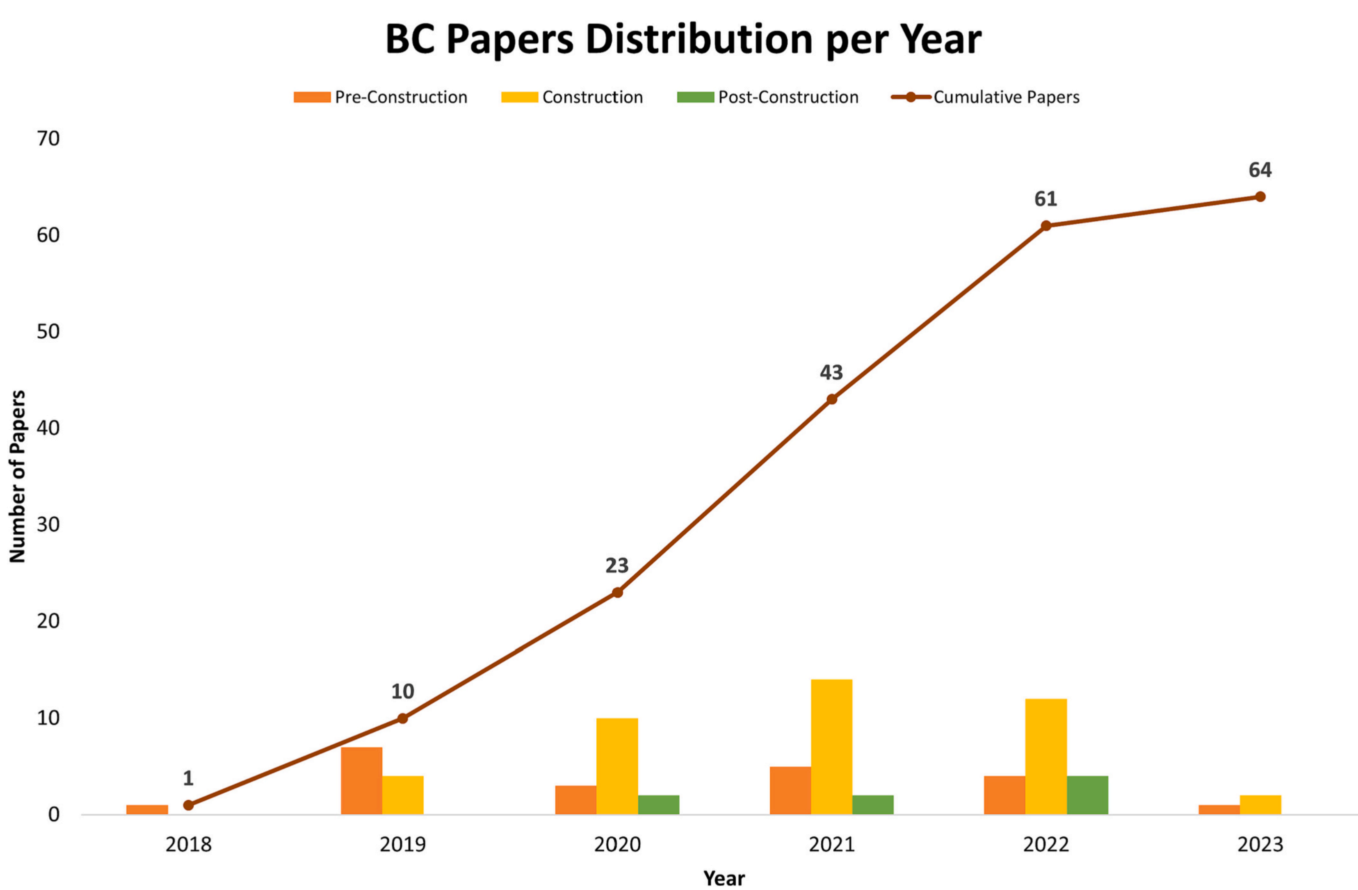

Fig. 5. Blockchain Papers' Trend Base on Publication Years.

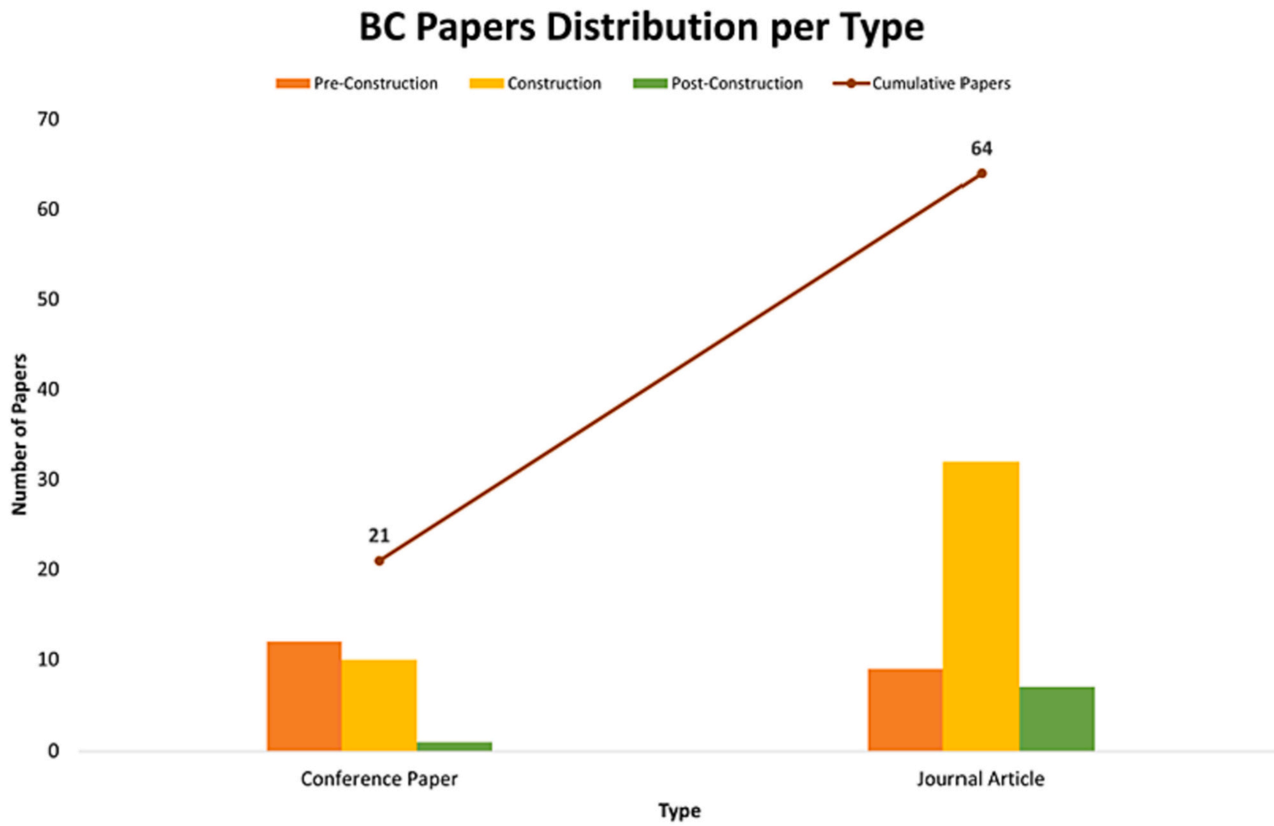

Fig. 6. Blockchain Papers' Trend Based on Document Types.

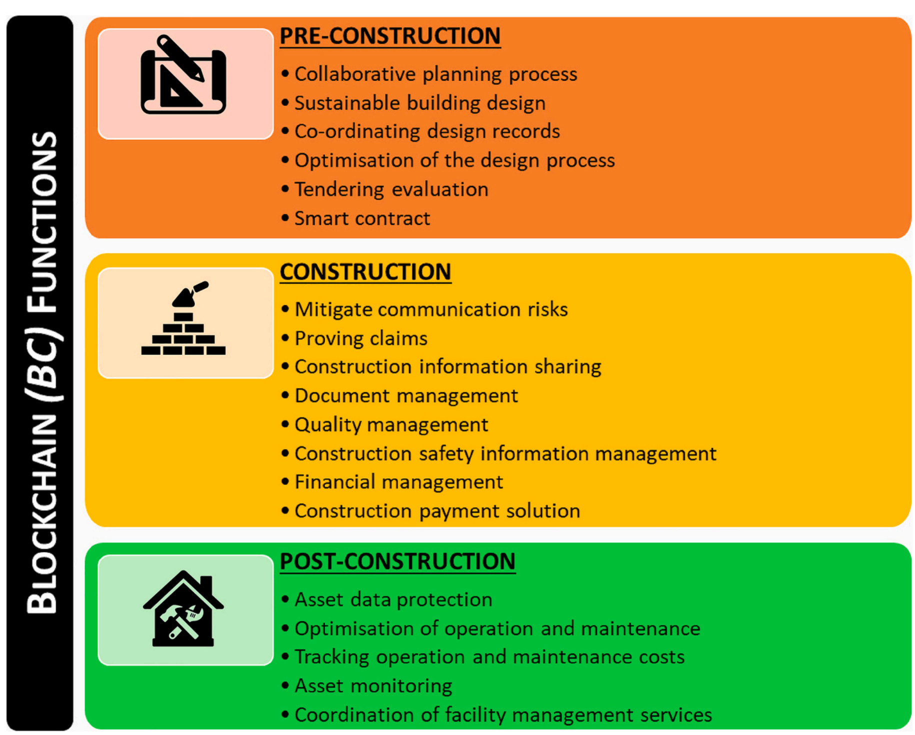

Fig. 7. Areas of Blockchain Applications in AEC-FM Literature.

information management to enhance collaboration during an intelligent building's planning process. Findings from the study indicated that employing decentralised ledgers can reinforce the quality and consistency of data for effective planning and enhance the security, accountability, and transparency of data. To overcome the problems of data tampering during preconstruction activities, Gong et al. [36] explored solutions to the e-tendering process by creating a secure blockchain-based evaluation framework to secure data during e-

Table 4
Overview of Blockchain Application Themes from AEC-FM Literature.

Building Lifecycle Phase	No of Studies	BC LITERATURE Authors/References
BC for Preconstruction	19	([6], [8], [10], [18], [23], [25], [27], [28], [26], [36], [41], [52], [55], [74], [90], [91], [124], [125], [148])
BC for Construction	44	([3], [8], [9], [11], [15], [17], [18], [20], [21], [30], [31], [32], [35], [43], [42], [52], [53], [59], [60], [66], [69], [70], [78], [80], [72], [81], [88], [89], [93], [100], [105], [108], [112], [117], [118], [119], [120], [131], [136], [140], [144], [149], [150], [151])
BC for Post-Construction	5	([40], [47], [104], [108], [128])

bidding. The proposed framework contributed to realising a fast-tendering evaluation process by keeping data immutable and traceable.

Celik et al. [10] further explored the potential of a BC-based BIM framework during the design phase of the life cycle of a built asset as a potential solution to facilitate collaboration. According to the authors, integrating BC technology with BIM will ensure higher data traceability, enhance project transparency, and encourage greater participant participation. Zheng et al. [148] further posit that a BC-BIM model can assure the integrity and provenance and improve the quality and security of BIM data. Dounas et al. [28] also believe that a BIM-BC framework is critical to the architectural design process due to its ability to record all attempts during the design process contributing to the optimisation of the design process and enhancing collaboration among design participants.

Di Giuda et al. [23] studied a smart contract embedded BC in the design phase to address the increasing fragmentation and complexity of projects and revolutionise the traditional way of contracting. The proposed study contributes to the realisation of a data-driven predictable process to support the efficiency of the process, reducing time for payout and protecting the entire supply chain against bankruptcy. Guo et al. [41] proposed a BC-smart contract framework to promote the sharing of data and the protection of intellectual property among designers of large-scale projects. BC-based smart contracts have the potential to authenticate, verify and execute autonomous sharing of BIM data with copyright protection [41].

4.4.2. BC for construction

Construction-related data are deemed vital in proving claims [60]; thus, recording, storing and managing data created while executing construction-related activities should be done based on trust between participants in a project [60]. Das et al. [21] proposed a BC-based management framework to improve accessibility and to share trusted and reliable information among participants in a network. The proposed framework leverages BC technology to enhance data integrity in document management during construction-related activities. Kim et al. [60] suggested that a BC-based system for construction document management could prevent the loss of construction-related data, prove valid contractual rights and support the reliability of claims and dispute-related tasks. BC can also ensure that construction-related data is traceable, immutable, and shared among project participants without an intermediary [66].

Li et al. [69] believe that successful cases of BC in other industries regarding quality management and traceability can be replicated in construction-related activities to aid in minimising disputes. Sheng et al. [117] developed a BC-based framework to help secure, consistent, and reliable capturing and documentation of construction site quality information to enhance trust and openness among project participants. The suggested framework benefits from BC's technical characteristics of ensuring that the quality information captured is traceable and cannot be altered. Furthermore, Li et al. [69] believe that employing BC mechanisms in construction-related activities can optimise quality management while ensuring data safety, reliability, and traceability. BC's implementation can also help solve traditional paper-based construction quality management issues by reducing errors and processing time for documents while improving information credibility [70].

To address unfair payment practices in the industry, Das et al. [20] proposed a blockchain framework to facilitate the transparent sharing of payment-related information, facilitate trust between contracting teams and automate conditions of payments using smart contracts. The proposed framework deploys BC to enhance security and transparency and facilitate the execution of payments. Corroborating BC's capabilities, studies by Elghaish et al. [31] showcased the capabilities of BC technology in enhancing trust and transparency among project parties via the development of an automated financial system to address the financial management of transactions among project participants. From a similar perspective, Hamledari and Fischer [42] introduced integrated BC-enabled smart contracts and robotic reality capture technologies for autonomous payment solutions for construction projects. The authors argue that the features of BC and smart contracts to decentralise and guarantee payments have the potential to address manual and heavily intermediate workflows around the execution of payments in the construction industry.

4.4.3. BC for post-construction

BC for post-construction activities mainly focused on using BC for asset data protection, optimisation of operation and maintenance, tracking operation and maintenance costs, asset monitoring, and coordination of facility management services.

According to Hijazi et al. [47], utilising BC's potential in providing trusted data presents the opportunity to transition from siloed databases towards an environment where databases are linked. BC can allow valuable data to be incorporated into post-construction activities such as operation and facilities management to contribute to a reliable digital output. Raslan et al. [104] created a BC platform to help protect an asset's data and enhance the functionality of Asset information models. Findings from the study indicate that applying BC in the management of Assets will improve decision-making and optimise assets' operation. Furthermore, BC can allow full access and tracking down purchases made for operating and maintaining an asset [104].

Facility management services are deemed critical to routine and real-time operations of a building hence the development of a BC-based smart contract by Tiwari and Batra [128] to enable the coordination of repairs and other facility management services in a smart building environment. According to the authors, the BC-based smart contract system may eliminate the need to outsource the management of a facility to a third party and further help expedite automation, security, and transparency in a smart building environment. Studies by Teisserenc and Sepasgozar [126] indicate that BC-enabled DT can support data decentralisation and enhance data traceability, security, and privacy. The authors posit that employing BC-integrated DT will allow facility managers to monitor an asset in real-time and effectively contribute to the automation and prediction of maintenance activities.

5. Discussions

An integrated discussion on the outlined research objectives in Section 1 is performed here by mainly focusing on combined findings about DT and BC applications within the construction industry from Section 4. Additional insights are discussed on the individual and combined characteristics that make them viable for enhanced building lifecycle management. Finally, knowledge gaps are identified for potential future research that authors deem necessary to explore harnessing the combination of BC and DT technologies across the entire building lifecycle.

An indicative state-of-art landscape on DT and BC applications in the AEC-FM emerged from the reviewed literature included in this study. Findings in this study also provide evidence that efforts and interests within DT and BC have gained increased attention within 2019–2022

(108 papers). Within that same period, the observed years of publications were 2020–2022 (98 papers), and they collectively represent about 90% of DT and BC studies within the AEC-FM context. Interestingly the proportion of document types favoured conference papers within 2020 (59%), but this switched in favour of journal articles from 2021 (64%) and 2022 (79%), which suggested an increasing pattern of research rigour for peer-reviewed journals on DT and BC studies.

5.1. State-of-art DT applications within the context of preconstruction, construction, and post-construction lifecycle phases

Findings on DT functions for a building's lifecycle have shown increasing research in the field of DT. Studies have indicated the potential benefits to be derived from the implementation of DT during each lifecycle phase. Studies retrieved predominantly focused on construction-related activities compared to the other lifecycle phases. There is also emerging attention to preconstruction activities, which may suggest attention to the early incorporation of DT during the development of a built asset. The authors speculate that the discovered pattern relating to the use of DT within both the construction and post-construction phases could be related to the need for an existing physical artefact to twin as a digital equivalent. This may clarify the few studies on DT within the preconstruction phase. However, these results contradict previous studies by some scholars like Opoku et al. [95], who found that DT research primarily focused on preconstruction activities such as design and engineering.

Furthermore, Opoku et al.'s (2021) research indicated a lack of literature on DT applications in the construction phase. These disparities may be due to the different time frames considered for literature retrieval. Opoku et al. [95] analysed studies conducted between 2010 and 2020, resulting in 22 relevant papers. In contrast, this study reviewed DT studies conducted from 2018 to the end of 2022, resulting in 48 papers. Despite these differences in findings, both studies confirm the growing interest in DT research.

5.2. State-of-art of BC applications within preconstruction, construction, and post-construction lifecycle phases

Studies on BC's use for the different phases of a building's lifecycle have rapidly grown, with most of the dominant studies focusing on preconstruction and construction activities, whilst the attention on post-construction activities seems to be emerging. BC's integration was considered suitable for any phase dealing with data management and smart contracts, thus invariably making it ideal for managing each phase in a built asset's lifecycle. Similarly, and extendedly over the snapshot years (2018–2023), most discovered studies in this review were published after 2018, with a dominant focus shift from the preconstruction phase to the construction phase. There is rapidly emerging attention for post-construction applications, which may suggest an appreciation for having accurate decentralised information throughout a building's lifecycle. Similar BC review studies by Scott et al. [113] reinforce the growing interest in BC studies. The study found that the publication of new literature on BC increased by a significant rate of 184% between 2017 and 2020.

5.3. Identify the complementary features of DT and BC necessary for enhanced building lifecycle management

Studies on the various functional aspects of DT have revealed unique characteristics that can enhance the value and outcome of integrating DT in all stages of a building's lifecycle (see Fig. 8). The identified features of DT from these studies include its ability to analyse and visualise data, capture real-time information, optimise processes, simulate scenarios, and make predictions. These distinct features align with existing literature and have the potential to improve collaboration, decision-making, and resource management, leading to efficient and effective management of each phase of a building's lifecycle [4,95,141].

Meanwhile, BC's consensus mechanism, decentralised capability, security, immutability, privacy, and data provenance are the distinct features that emerged from the studies analysed. These distinct features can enhance collaboration, enhance trust and transparency between project participants, enhance decision-making and contribute to improved management throughout a building's lifecycle. Findings on BC's distinct features are further reinforced by literature highlighting the potential of BC to contribute to better resource management, eliminate disputes and reduce costs [68,113].

An overview of the distinct characteristics of both DT and BC reveals a perspective which reinforces the potential for DT and BC integration to

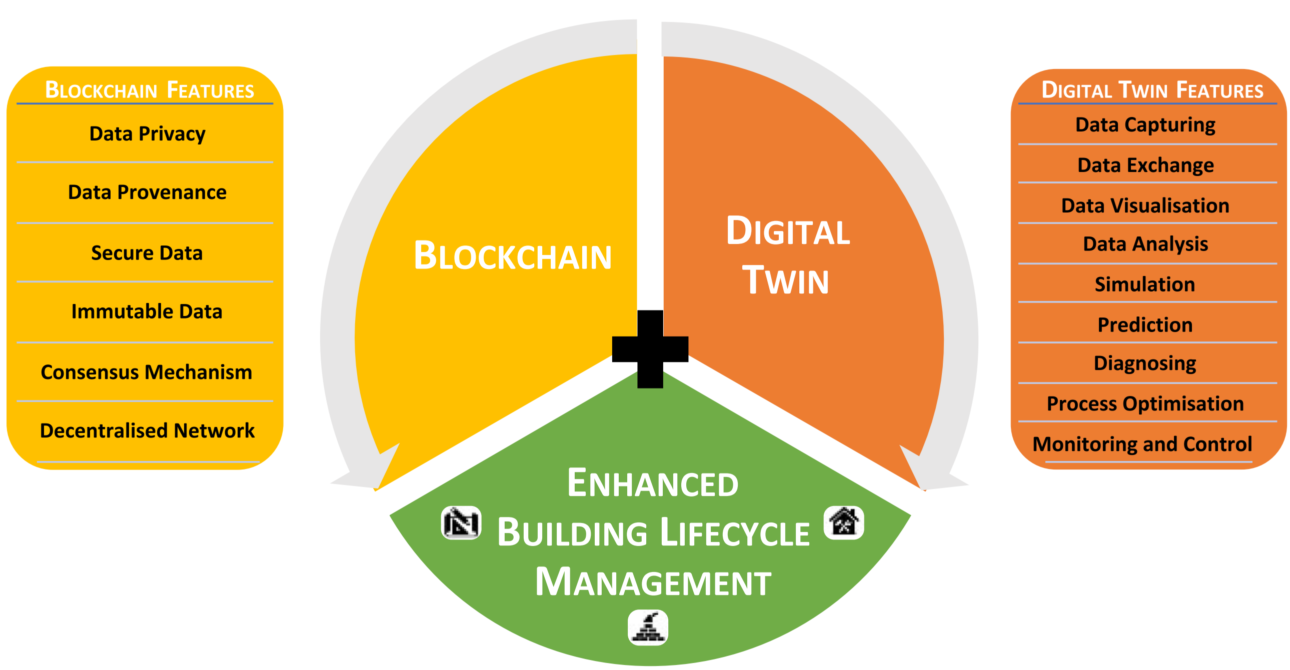

Fig. 8. Features of Digital Twin and Blockchain identified from AEC-FM Literature.

support collaborative work practices by establishing enhanced communication among stakeholders, sustaining secure data integrity and an authentic environment within the digital space to represent the physical artefact or process that it aims to twin. Furthermore, the study's findings reveal that DT and BC can demonstrate real-time project status monitoring and provide data provenance throughout their lifecycle. It can tactfully predict future occurrences and realise data-driven intelligent forecasting practices. In line with that, DT and BC bring on board management implications that can be harnessed for real-time data monitoring, secure data and information exchange, trustworthy and transparent decision-making, process automation to eliminate paper-based clutter and human errors, as well as mitigate poor data utilisation when faced with excessive sources of data. The assumptions drawn on the joint capabilities of BC and DT integration are supported by Putz et al. [101], who indicate that attributes of BC and DT have great potential to benefit a building's lifecycle. Therefore, BC-based DT applications could enhance the management of every phase of a building's lifecycle.

5.4. Highlight research gaps identified for both DT and BC applications within the context of building lifecycle phases

Based on the above discussions and efforts identified in the literature, the following gaps were identified, especially relating to the perspectives of building lifecycle management, to propose future research directions.

Despite the identified efforts by DT and BC studies across pre-construction, construction and post-construction phases, less attention is paid to the transition between construction and post-construction concerning handover activities, deemed very critical in a building's lifecycle [154]. Handover activities require more attention since it involves transferring vital information from the construction team to the facility management team and require a consolidated database of information about the built asset as a source of reliable data to enhance post-construction management activities [83]. Additionally, as rightfully identified by RIBA [107], the building handover comprises activities where data is validated and signed off; hence data handed over must be up-to-date, available and accurate to enhance the efficient management of a built asset. The authors propose a need to address the research deficiency within the handover stage by mobilising studies to focus on exploring, understanding, and harnessing the potential of DT and BC to address this knowledge gap.

Furthermore, studies have revealed the potential role of DT and BC regarding collaboration in a decentralised and immutable manner, bringing into perspective their suitability within the AEC-FM industry due to the dispersed stakeholders involved. These stakeholders require credible large volumes of data or information to make informed decisions about design, planning, construction, utilisation, and maintenance. This reinforces the complementary nature of DT and BC, especially when dealing with critical verification of information and positioning the assets for usage or maintenance activities. Accordingly, there remains a void that tests these hypothetical promises and challenges using empirical research data from qualitative and quantitative methods to elucidate robust knowledge discoveries to deepen the understanding and create awareness about DT and BC for managing building lifecycle activities within the AEC-FM industry.

5.5. Limitations of the study

Although this study provides valuable insights, it is essential to note that the findings should be viewed in the context of certain limitations. Due to the study's focus on building lifecycle management, publications retrieved were limited to that area, warranting detailed exploration at each respective phase. Thus, other review studies should consider delving deep into other areas or activities within the AEC-FM industry to gain more valuable insights and enrich the knowledge on the potential of DT and BC.

From a methodological or procedural perspective, the literature retrieval for this study was limited to Scopus and Web of Science databases and filters for retrieval were restricted to English language, journal papers, and conference papers. It is anticipated that different results may exist in different databases, different languages, or document types (e.g., books or thesis reports). Therefore, an extended, systematic search in other relevant literature databases is anticipated to uncover different results. Additionally, due to the rapidly increasing focus on DT and BC in the industry, further reviews could consider investigating literature published outside the time frame in which this study was conducted.

The limitations highlighted above provide opportunities for further study and should be considered when replicating this study or conducting comprehensive studies. Nonetheless, the outcomes of this study have laid a strong foundation and provided valuable insights into the capabilities and possible uses of DT and BC in effectively managing the lifecycle of buildings.

6. Recommendations

This research thoroughly examines how DT and BC can be utilised at various stages of a building's life cycle in the AEC-FM industry. By analysing the unique features of both DT and BC, it becomes evident that integrating them can result in capabilities like real-time data monitoring, secure information exchange, reliable decision-making, process automation, and improved data utilisation while reducing paper-based clutter and errors. As a result, the study offers recommendations on how to leverage these potentials.

While there is a significant amount of literature on DT and BC, only a limited number of studies delve into their integration. To fill in these gaps and enhance knowledge of their practicality, more research is necessary to examine and justify their potential. Additionally, further investigation could be carried out to identify the enabling technologies and the critical requirements that would facilitate the implementation of DT and BC solutions for the construction industry. Moreover, this study has primarily focused on the enabling capabilities of combining DT and BC for the AEC-FM industry; however, their integration comes with numerous challenges worth exploring to provide a holistic perspective that result in informed decisions on their joint relevance before adoption.

This paper focused on the three main building lifecycle phases (preconstruction, construction, and post-construction); however, each phase entails unique complexities and numerous stakeholders that are worthwhile exploring in detail to understand the contextual opportunities and threats which affect the combined application of DT and BC within specific situations. It is also worthwhile obtaining multi-stakeholder perspectives on the associated relevance and anticipated challenges of employing both DT and BC within each building lifecycle phase.

Accordingly, testing their potential in real life is essential to effectively apply the integration of DT and BC in the AEC-FM industry. While most publications focus on theoretical methods for research purposes, further studies involving prototype development and practical approaches to adopting such solutions should be explored. A collaborative effort between academia and industry can demonstrate the real-world significance of these technologies. This approach not only promotes greater awareness of DT and BC but also improves stakeholders' perspectives and validates their potential and benefits to be derived.

7. Conclusions

This paper mainly addresses the previously mentioned gap of limited review studies on the potential integration of DT with BC technologies within the AEC-FM industry. It presents a comprehensive and critical overview of DT and BC application areas within the AEC-FM industry, focusing on building lifecycle phases (pre-, construction, and post-construction). The paper explored the distinct features from the retrieved DT and BC literature. It was discovered, from the reviewed papers, that potential uses of DT and BC encompass all building lifecycle phases, but the dominantly focused phase is the construction phase.

Findings revealed potential applications for DT, including planning and design decision-making, construction progress monitoring, construction safety, construction waste management, and monitoring asset operation and maintenance. Findings also indicated that research on BC for building lifecycle activities focused on using BC for planning and design collaboration, document management, quality management, construction safety information management, tracking operation and maintenance costs, and coordination of facility management services.

Based on the unique features of DT and BC technologies, the authors posit the potential for the collaborative use of DT and BC within the AEC-FM industry to enhance building lifecycle management. The complementary nature of DT and BC could tackle critical issues regarding stakeholder collaboration and information fragmentation within the AEC-FM industry.

Following the identified knowledge, context, and gaps regarding the role of DT and BC, the authors argue a justification for further multidisciplinary research to contribute to advancing such emerging technologies within the AEC-FM industry. Future work on combined DT and BC applications throughout a building's lifecycle may focus on gathering empirical evidence that supports a deeper understanding and adoption of these emerging technologies in the AEC-FM industry.

This paper is deemed useful for academics and practitioners to spot gaps or recognise the literature landscape on DT and BC. This study contributes valuable insights for practitioners in the AEC-FM industry and empowers decision-makers to grasp the significance of a DT-BC approach and predict its outcomes. Additionally, it serves as a comprehensive guide for those seeking to comprehend the potential of these emerging technologies and their integration and develop practical strategies for their adoption and implementation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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