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Enhancing asset management: Integrating digital twins for continuous permitting and compliance - A systematic literature review

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A R T I C L E I N F O

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A B S T R A C T

The emergence of Digital Twin technologies (DT) has revolutionised construction works and asset management, thereby improving efficiency and control through exceptional precision and operational transparency. In this paper, various DT applications in construction industries were investigated and focused on their ability in continuous permitting and compliance checking within the construction industry. A systematic literature review was conducted, retrieving 1698 documents from Scopus and Web of Science using keywords related to digital twins, construction, permitting, and compliance checking, where the PICO framework was applied, focusing on four key aspects: Population (construction industry), Intervention (digital twins), Comparison (traditional methods), and Outcome (efficiency and quality improvements in construction). This approach screened the relevant papers, and 80 publications were analysed and categorised into 8 categories: (Predictive Building Maintenance, Smart Building Asset Management, Building Energy Efficiency, Lifecycle Sustainability Assessment, Building Lifecycle Monitoring, Structural Health Monitoring, Safety Asset Management, and Stakeholder Management). The findings highlight DT's ability to enhance predictive maintenance, improve collaboration, and enable real-time energy optimisation, driving economic growth and streamlining construction. This paper aims to fill the gap by reviewing the various ethical limitations, emphasising data privacy; technical limitations, emphasising data quality; and operational limitations, focusing on continuous permitting and compliance checking. Future research should focus on developing comprehensive strategies to address these challenges and leverage these advancements for enhanced knowledge and asset management. This study provides insights for policymakers, scholars, and practitioners, emphasising the transformative potential of DT technologies in construction and their role in advancing the Fourth Industrial Revolution.

1. Introduction

Since the discovery of DT technology, the field of asset management and construction has been transformed. The technology has allowed for extraordinary improvements in operational control, precision, and efficiency [1,2]. In the 1960s, NASA developed the concept of a digital twin, which was a living model of the Apollo mission. This was the first of its kind, allowing for continuous analysis of the data collected during the mission [3]. The rapid emergence and evolution of digital technology have greatly changed the way

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Abbreviations

DT	Digital Twin
BIM	Building Information Modelling
IoT	Internet of Things
AI	Artificial Intelligence
AR	Augmented Reality
GIS	Geographic Information System
SHM	Structural Health Monitoring
LCSA	Lifecycle Sustainability Assessment
4IR	Fourth Industrial Revolution
XR	Extended Reality
HBIM	Heritage Building Information Modelling
BC	Blockchain
FM	Facility Management
ML:	Machine Learning
O&M	Operation and Maintenance
KPI	Key Performance Indicator
AM	Asset Management
FE	Finite Element
IFC	Industry Foundation Classes
OPW	Ontology for Production Workflow
AEC	Architecture, Engineering, and Construction

traditional industries operate as it has the tendency to improve efficiency and access information more quickly [4]. Where DT theory was first introduced in 2003 by Professor Grieves at the University of Michigan, and scholars have covered the technology's various phases ever since, such as digital mapping and digital mirrors were defined by Attaran et al. (2023) [5]. Global academic collaborations and research initiatives, supported by journals, conferences, and consortia, have played a pivotal role in shaping the development of Digital Twin technologies. These initiatives have facilitated the practical adoption of DTs across industries, ensuring their alignment with the demands of modern construction and asset management practices [1,2,5,6]. Additionally, in Industry 4.0, digital twins are widely used to improve construction efficiency by allowing it to exchange and analyse data [7]. With regards to asset management, especially for continuous permitting and compliance checking in construction; using Digital Twin technology is a prime example of the Fourth Industrial Revolution's impact [6].

A continuous compliance and permitting process ensures that construction projects follow all the necessary regulations and codes throughout their entire lifecycle and bring advantages to the built environment [8,9]. Unlike traditional permitting methods, which typically involve carrying out inspections at certain stages, continuous compliance checks utilise real-time data and systems to monitor a project's compliance continuously, thereby increasing the maturity of asset information models [9,10]. This approach can result in a

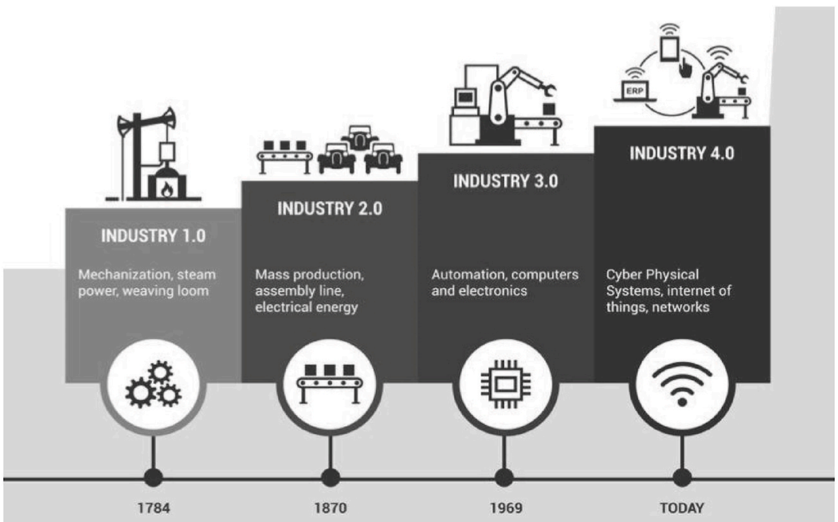

Fig. 1. Each era transformed manufacturing (adopted: Mohamed et al. (2024) [13]).

more streamlined and productive project, as it eliminates time-consuming traditional methods and ensures that buildings follow certain technical standards.

From the First Industrial Revolution (mechanical production) to the Fourth Industrial Revolution (Industry 4.0), each era transformed manufacturing, as shown in Fig. 1. These innovations resulted in the development of intelligent systems that improved the flexibility and adaptability of production [11]. The Fourth Industrial Revolution has been one of the main factors that has led to the transformation of society in the 21st century [11,12]. This revolution is marked by the convergence of digital, physical, and Bioengineering, including the Internet of Things, artificial intelligence, and autonomous vehicles [13,14]. Digital twin technology, a critical component of the Fourth Industrial Revolution, plays a central role in transforming traditional industrial processes by integrating the physical and digital worlds through real-time data collection, advanced simulations, and predictive analytics to optimise design, construction, and asset management processes [6]. By creating digital replicas of physical assets, construction projects can leverage Digital Twin models to monitor the condition of equipment and infrastructure, predict potential issues before they occur, and make data-driven decisions throughout the project lifecycle. This leads to enhanced collaboration, reduced errors, minimised downtime, and more precise project planning [15,16]. Numerous chances for businesses to grow and innovate are offered by Industry 4.0. Technological advancements such as Artificial Intelligence "AI", Big Data, Machine Learning "ML", and the Internet of Things "IoT" are expected to play a vital role in the technology's implementation, which can also help improve environmental sustainability [17]. These technologies collectively form an operational ecosystem that supports the implementation of Digital Twins. For instance, IoT sensors provide real-time data streams to update the DT models [18], AI-driven analytics enable predictive maintenance and anomaly detection [19,20], Big Data ensures the integration of large datasets for comprehensive monitoring [21], and ML algorithms optimise decision-making by learning from historical data to make accurate predictions [22]. Together, these technologies allow DTs to function as dynamic and interactive models that facilitate real-time compliance monitoring, resource optimisation, and process automation in the construction industry.

As integral components of the Fourth Industrial Revolution (4IR), these technologies can revolutionise conventional building methods by incorporating digital or physical assets, while giving a room for real-time monitoring and predictive maintenance [23].

Klaus Schwab, founder and executive chairman of the World Economic Forum, states, "*The world has the potential to connect billions more people to digital networks, dramatically improve the efficiency of organisations and even manage assets in ways that can help regenerate the natural environment, potentially undoing the damage of previous industrial revolutions*." [24].

Integrating DTs with Industry 4.0 technologies has enhanced project management and the lifecycle of buildings [25]. The evolution of technological innovations has been involved in the growth of the global economy, and their use in various sectors has been estimated to have contributed in developing new economic models [26]. Despite the technological advancements that have been made in the field of digital technology, DT remains a relatively new concept. It is still used in simulating "what-if" scenarios that can occur in real-world environments [27]. For instance, by allowing people to monitor and control a system, a DT can help improve the Continuous Permitting and compliance checking process. Noteworthily, traditional Asset Management (AM) was mainly done on reactive strategies and heavily relied on scheduled maintenance [28]. With the emergence of Industry 4.0, this approach is shifting toward more proactive and predictive methods [29,30]. Despite the innovations in DT technology, there has been insufficient consideration of the various ethical, technical, and operational issues that affect the use of this technology in continuous permitting and compliance checking.

As digital twins are increasingly used to monitor construction sites, significant limitations arise in ensuring adherence to local building codes, environmental regulations, and safety standards. Compliance rules vary noticeably by jurisdiction, and continuously updating a Digital Twin to reflect regulatory changes is complex [23]. For instance, if local safety regulations change during construction, the system must rapidly adjust to avoid violations. This requires not only a sophisticated Digital Twin infrastructure but also close collaboration with local authorities, which can be challenging to coordinate [31]. Moreover, one of the long-term objectives of integrating Digital Twin technology into construction is the complete automation of permitting processes. However, ensuring that all the data required for permit approval, such as environmental impact reports, structural integrity tests, and safety audits—is accurate and up-to-date presents a significant challenge. Automated systems could potentially approve permits without the necessary human oversight, leading to compliance risks [32].

Additionally, regulatory environments are highly fragmented in real-world applications. Each local government, municipality, and building department has unique requirements, leading to complications when scaling Digital Twin applications across regions [33]. For example, one city might prioritise frequent environmental monitoring, while another focuses on worker safety protocols. Standardising compliance checks across multiple jurisdictions using Digital Twins is a significant challenge that requires unified frameworks and collaboration. Also, regulatory fragmentation and strict data protection laws, like GDPR in Europe, hinder the scalability of Digital Twin applications. Unified frameworks and compliance strategies are essential to address diverse regional requirements and unlock the potential of Digital Twins in permitting and compliance [34]. Addressing these challenges is critical for unlocking the full potential of Digital Twins in revolutionising permitting and compliance processes.

Insights from supply chain management, such as performance frameworks and diffusion models, offer valuable parallels to the challenges faced in scaling Digital Twin (DT) applications. For instance, studies on prefabricated housebuilding highlight the importance of integrated performance frameworks [35], relational modelling for stakeholder collaboration [36], and the application of supply chain management theories to improve organisational performance [37]. The performance dimensions in prefabricated housebuilding supply chains, such as time, cost, quality, and innovation [36], provide insights into optimising DT frameworks. Similarly, supply chain management reviews emphasise themes like data-driven decision-making, scalability, and cross-disciplinary interventions [37], which aligns with the integrated strategies required for DT technologies. Lessons from these interrelationships can help address fragmented regulations and enhance permitting and compliance processes in construction. This study addresses these challenges by evaluating the ethical, technical, and operational issues in DT implementation. By drawing insights from related fields and proposing unified frameworks, it seeks to unlock the full potential of DT technology in revolutionising permitting and compliance processes in the construction industry.

2. Methodology

A systematic review approach will be conducted on enhancing asset management, specifically a study of using digital twins as a methodology for delivering the building's continuous permitting and compliance checking/monitoring. Additionally, the review explores the various technological limitations and operational challenges that can affect the use of DT in construction. Understanding these issues is crucial to developing effective strategies and successfully overcoming them [29]. This addresses a significant research gap, as no prior studies have explicitly focused on leveraging DT for continuous permitting and compliance. Instead, this review will focus on using DT technology in construction. The study also follows the PRISMA framework shown in Fig. 2. This framework is a widely used methodology designed to enhance the transparency and reproducibility of systematic reviews. It provides a structured approach to identifying, screening, and selecting studies relevant to a specific research question, ensuring a comprehensive and unbiased analysis as discussed in stage 1, stage 2, and stage 3 below [38].

Moreover, the review will go further to answer the research questions below and examine the strengths and limitations in each of these areas. This paper will provide a thorough understanding of how DT technologies can transform construction practices and contribute to the advancement of the industry.

1 Do digital twin technologies significantly improve efficiency and quality in construction processes over traditional methods, especially in construction permitting and compliance?

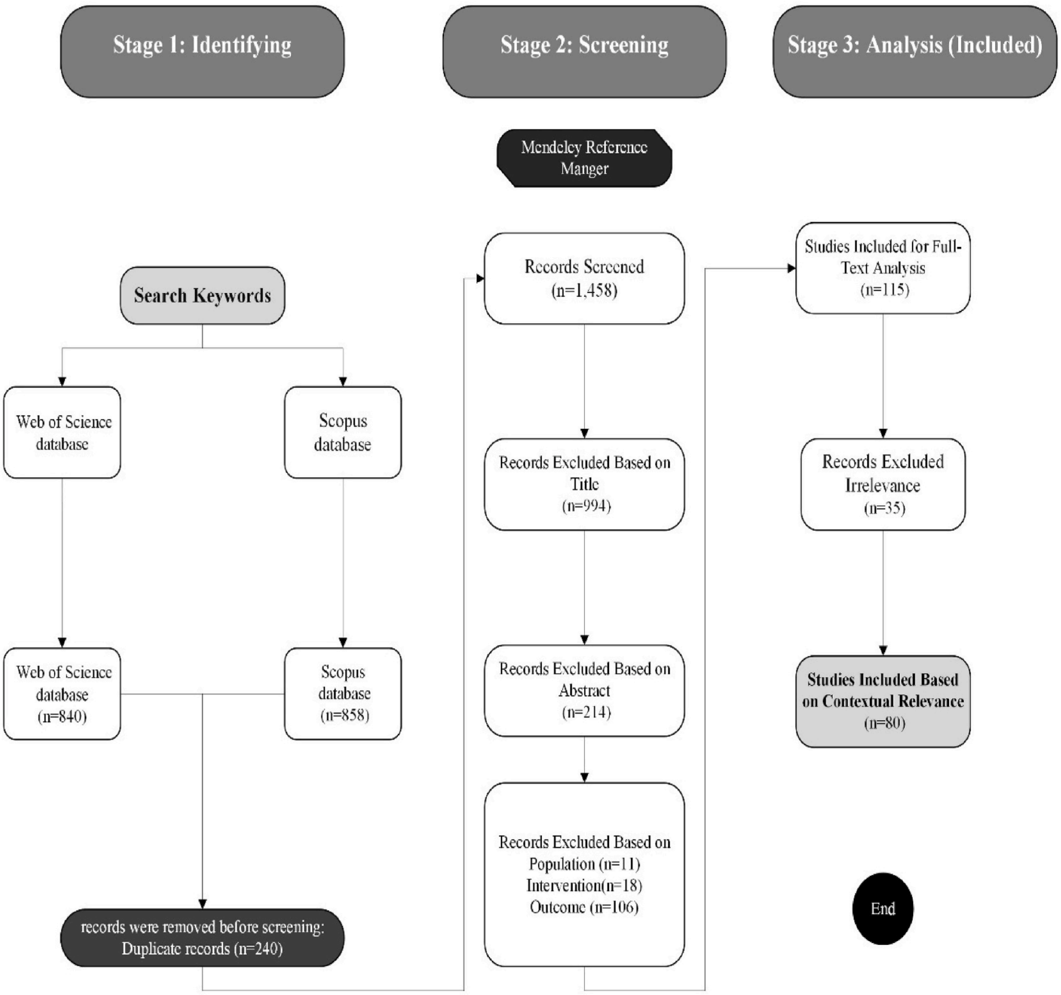

Fig. 2. " The PRISMA framework for the study."

2 Considering their implications for economic growth, how do these technologies integrate into asset management within the context of the Fourth Industrial Revolution?
3 What are the future research needs and goals for further developing and implementing digital twin technologies in construction, especially in asset management?

2.1. Stage 1: identifying recent reliable research publications using databases and search engines

The systematic literature review references have been commenced from Scopus (840) and Web of Science (858). The following keywords are identical but formed differently based on the syntax for the databases that were selected to provide a broad perspective to address the posited research questions.

Database	Queries
Scopus	(TITLE-ABS-KEY (“Digital Twin*" OR “Digital asset*" OR “asset*") AND TITLE-ABS-KEY (BIM OR “Building Information Modeling”) AND TITLE-ABS-KEY (“Build*" OR “Construct*") OR TITLE-ABS-KEY (“Building permit*" OR “Building compliance checking” OR “Building control*")) AND PUBYEAR >2019 AND PUBYEAR <2025 AND (LIMIT-TO (SUBJAREA, “engi”))
Web of Science	"Digital Twin*" OR “Digital asset*" OR “asset*" (All Fields) AND “BIM” OR “Building Information Modeling” (All Fields) and “Build*" OR “Construct*" (All Fields) OR “Building Permit*" OR “Building compliance checking” OR “building control*" (All Fields) and 2020 or 2021 or 2022 or 2023 or 2024 (Publication Years) and English (Languages) and English (Languages) and Engineering or Construction Building Technology or Architecture or Urban Studies (Research Areas)

These keywords helped find studies that examined how digital twin technologies improve continuous building and construction permitting and compliance checking. Focusing on publications from 2020 to 2024 confirms that the review reflects the latest advances in the field. This approach matches the study’s aims to assess how digital twin technologies integrate into asset management to enhance construction projects’ efficiency, quality, and economic impact in the context of the Fourth Industrial Revolution.

A wide range of two collections of peer-reviewed literature from diverse database fields, Scopus and Web of Science, were used to search for relevant and recent studies published between January 1, 2020, and March 21, 2024, relating to engineering or construction building technology. Mendeley Reference Manager was used to manage the references, and Excel helped with data analysis by filtering, effectively handling citations, and sorting large amounts by criteria such as PICO. This is because, with regard to asset management and continuous permitting in the construction industry, the PICO framework utilises evidence-based research that is adapted to structure and enhances the understanding of how Digital Twin (DT) technology supports these practices. The PICO element, Population, Intervention, Comparison, and Outcome can help explain how integrating Digital Twin technology addresses critical challenges in asset management and regulatory compliance [39], guaranteeing a systematic literature review.

The search returned 1698 documents, including journal articles, conference papers, and book chapters. After removing 240 duplicate sets with identical DOIs, 1458 references were left.

2.2. Stage 2: screening and retaining relevant publications

Based on the study research question, how can digital twins streamline the permitting process and enhance compliance monitoring by using digital models of a physical asset to reduce the need for physical inspections, and how does this contribute to advancing asset management in the context of the Fourth Industrial Revolution? A PICO framework which sets the scope for systematic literature reviews aligns boundaries with goals and offers a structured research methodology review approach [40]. It was developed to guide the screening of the documents at different stages include Full title screening, Abstract screening and Contextual screening. The contexts of the retrieved articles were reviewed using the PICO criteria to evaluate the study’s eligibility as well as their context. The PICO criteria represent the following.

- **Population**: The construction industry, specific projects, organisations/governments.
- **Intervention:** Using digital twins, digital assets, or BIM-based permitting to see the implementation of DT technologies for real-time permitting and compliance monitoring in construction projects.
- **Comparison:** Traditional permitting and compliance processes that rely on manual and periodic inspections (if found*).
- **Outcome:** Enhanced efficiency, transparency, quality and data-driven decision-making in asset management and regulatory compliance.

This structured approach allows the review to align evidence-based findings with the challenges and opportunities in using DT technology for asset management and compliance.

2.3. Stage 3: analysing relevant digital twins or digital asset use cases applied to buildings and analysing their underpinning

This stage will involve reviewing the 115 articles and extracting information that answers the research question. The data to be extracted includes the author, the intervention (DT, BIM-permitting process), the use or application of the intervention, the method of application, the limitations of the intervention, the outcome of the findings, and suggestions for further studies. This is to create a general overview of each article's content and group the articles based on key focus areas for an in-depth discussion that answers the research question. At the end of this stage, **80 articles** were found relevant and included in the study's final discussion. This stage will focus on conducting a detailed analysis of the selected 80 articles, categorised after reviewing the papers into eight thematic areas: Predictive Building Maintenance, Smart Building Asset Management, Building Energy Efficiency, Lifecycle Sustainability Assessment, Building Lifecycle Monitoring, Structural Health Monitoring (SHM), Safety Asset Management, and Stakeholder Management. These categories were chosen based on their coverage of the most critical aspects of construction especially in asset management. To systematically categorise the selected publications, recurring themes in the literature were identified and aligned with the study objectives and research questions. This approach provides a structured understanding of Digital Twin (DT) technologies' current focus and their contributions to the field. These themes were selected to address the research questions and highlight key areas where DT technologies can transform construction practices and asset management. As shown in Table 1, the categorisation ensures that the study captures the diverse applications and limitations of DT technologies in construction, emphasising their relevance to the study objectives and the broader goals of the research.

The findings will be presented using various tools, such as diagrams, summary tables, and bibliometrics. In addition to that, each article was analysed for technologies used or integrated with DTs, enabling a more comprehensive evaluation. More so, the discussion section will include a summary of each category topic to focus on its limitations and strengths. This analysis will provide a comprehensive evaluation of the advantages of utilising DT technology in improving the efficiency and quality of construction. It will also explore their integration into asset management within the context of the Fourth Industrial Revolution, thereby addressing the research questions comprehensively.

4. Discussion

Traditional methods of quality control in construction are often prone to inaccuracies, which is why digital tools are replacing them [52]. These traditional techniques have been used for a long time in the construction industry. A building's dynamic and static characteristics can be replicated in real-time through DT as digital assets. This method can predict the building's future state and monitor its current condition [68]. DT is revolutionising the construction industry by significantly improving efficiency and quality compared to traditional methods, especially in construction continuous permitting and compliance checking.

Also, DT technologies are not just enhancing asset management but are setting new standards to improve the maintenance and optimisation of assets in connected industries. Furthermore, the implications of DT technologies for economic growth are profound. In the Fourth Industrial Revolution context, these technologies integrate seamlessly into asset management systems, enhancing industries' capabilities to manage their resources more effectively. The rapid emergence and evolution of DT technologies have shifted from traditional asset management methods to a more modern form of smart construction [69].

4.1. Digital Twin for smart-building asset management

Implementation of DTs in smart building management has prompted for better control over the various operations of a facility as it improves the efficiency of the building's overall management [45,48,49]. The studies of [46,47,49] and other researchers in Table 4 summarise the strengths and limitations of SBAM for the 4IR technologies in building and asset management systems, especially DT. Their discussion includes the use of 3D scanning, digital mapping, and photogrammetry, and it was stated that these technologies can help improve the efficiency of building operations by allowing them to collect and visualise data. One of the main advantages of these systems is the ability to provide continuous monitoring and improve the decision-making process. Despite these various advantages, many barriers still prevent them from being widely used. These include the complexity of implementation, the need for more training and support, and the dependence on specific software.

Additionally, one significant challenge to wider adoption is the integration of DT platforms with existing Building Information Modeling (BIM) systems. BIM is a foundational tool for managing building design and data. Still, its interoperability with real-time IoT sensor data in Digital Twins is often complex due to a lack of standardised protocols and formats. To address this, open standards like Industry Foundation Classes (IFC) and middleware platforms can facilitate seamless data exchange between BIM and DT platforms. Furthermore, collaborations between BIM and DT software providers can lead to the development of plug-ins for smoother integration [73,74]. Another critical barrier is data security and privacy concerns. Digital Twins relies heavily on data from IoT sensors, building

Table 1
Categories, focus, and references in digital Twin applications.

Categories	Focus	References
Predictive Building Maintenance	Forecasting and optimising maintenance needs	e.g. [41,42,43,44],
Smart Building Asset Management	Improving asset monitoring and operational efficiency	e.g. [45,46,47,48,49],
Building Energy Efficiency	Optimise energy consumption, reduce carbon footprints	e.g. [50,51,52],
Lifecycle Sustainability Assessment	Environmental, economic, and social impacts of buildings	e.g. [53–55],
Building Lifecycle Monitoring	Continuous real-time performance evaluations	e.g. [56,57,58,59],
Structural Health Monitoring (SHM)	Ensuring structural integrity and safety of assets	e.g. [60,61,62,63],
Safety Asset Management	Enhancing construction safety protocols	e.g. [64,65],
Stakeholder Management	Improved collaboration, transparency, and decision-making	e.g. [66,67],

Table 2
Summary table of findings - 80 articles.

Ref-ID	A group of technologies in the context of the Fourth Industrial Revolution (4IR)						Smart Building Asset Management	Safety Asset Management	Predictive Building Maintenance	Building Energy Efficiency	Lifecycle Sustainability Assessment	Building Lifecycle Monitoring	Structural Health Monitoring	Stakeholder
	DT	BIM	IoT	AI	AR	GIS	Smart Construction for Assets Management							
[121]		✓						✓						
[81]	✓	✓							✓					
[122]	✓	✓	✓		✓			✓	✓					
[45]		✓	✓				✓							
[99]	✓	✓	✓		✓	✓						✓	✓	
[41]	✓	✓	✓	✓			✓		✓					
[64]	✓	✓	✓	✓	✓	✓		✓						
[131]	✓	✓	✓	✓	✓		✓							
[50]	✓	✓	✓			✓				✓				
[132]	✓	✓	✓				✓							
[46]		✓	✓	✓			✓	✓						
[68]	✓	✓	✓				✓							
[71]	✓	✓	✓				✓							
[42]		✓	✓		✓				✓					
[82]		✓							✓					
[79]	✓	✓			✓				✓					
[60]	✓		✓										✓	
[43]	✓		✓	✓					✓					
[105]	✓	✓	✓	✓					✓				✓	
[44]	✓	✓	✓						✓	✓				
[90]	✓	✓			✓					✓				
[89]	✓	✓	✓							✓				
[91]	✓	✓	✓							✓				
[88]	✓	✓		✓						✓				
[87]	✓	✓	✓			✓				✓				
[51]	✓	✓	✓	✓						✓				
[53]	✓	✓	✓	✓							✓			
[54]	✓	✓	✓	✓							✓			
[55]	✓	✓	✓	✓		✓					✓			
[56]	✓	✓	✓									✓		
[112]		✓									✓			
[113]	✓	✓	✓	✓		✓					✓			
[47]	✓	✓	✓				✓					✓		
[101]	✓	✓	✓		✓	✓							✓	
[116]	✓	✓				✓						✓		
[133]	✓	✓	✓	✓		✓						✓		
[65]	✓	✓	✓	✓				✓						
[134]	✓	✓	✓									✓		
[135]	✓	✓	✓	✓	✓	✓						✓		
[136]	✓	✓	✓				✓							
[48]	✓	✓	✓				✓					✓		
[137]	✓	✓		✓								✓		
[72]		✓				✓	✓							
[120]	✓	✓	✓		✓	✓						✓		
[125]		✓				✓								✓

(continued on next page)

Table 2 (*continued*)

Ref-ID	A group of technologies in the context of the Fourth Industrial Revolution (4IR)						Smart Building Asset Management	Safety Asset Management	Predictive Building Maintenance	Building Energy Efficiency	Lifecycle Sustainability Assessment	Building Lifecycle Monitoring	Structural Health Monitoring	Stakeholder
	DT	BIM	IoT	AI	AR	GIS	Smart Construction for Assets Management							
[138]	✓	✓	✓			✓	✓							
[139]	✓	✓	✓	✓									✓	
[117]	✓	✓	✓	✓	✓	✓						✓		
[61]	✓	✓	✓	✓									✓	
[140]	✓	✓	✓	✓	✓	✓		✓						
[57]	✓	✓	✓	✓	✓	✓						✓		
[123]	✓	✓	✓	✓										✓
[58]	✓	✓	✓	✓		✓						✓		
[141]	✓	✓	✓	✓								✓		
[142]	✓	✓	✓	✓								✓		
[143]	✓	✓	✓									✓		
[59]	✓	✓	✓	✓	✓							✓		
[70]	✓	✓	✓	✓			✓							
[144]	✓	✓	✓				✓							
[80]	✓	✓	✓	✓					✓					
[145]	✓	✓	✓	✓								✓		
[69]	✓	✓	✓									✓		
[52]	✓	✓	✓	✓						✓				
[102]	✓	✓	✓										✓	
[146]	✓	✓	✓	✓	✓		✓							
[103]	✓	✓	✓										✓	
[66]	✓	✓	✓	✓										✓
[104]	✓	✓	✓	✓									✓	
[62]	✓	✓	✓	✓	✓	✓							✓	
[100]	✓	✓	✓										✓	
[147]	✓	✓	✓	✓									✓	
[63]	✓	✓	✓	✓	✓								✓	
[49]	✓	✓	✓				✓							
[148]	✓	✓	✓	✓									✓	
[124]		✓												✓
[126]	✓	✓				✓								✓
[67]	✓	✓	✓	✓	✓									✓
[149]	✓	✓	✓	✓	✓	✓	✓							
[98]	✓	✓	✓	✓		✓							✓	
[150]	✓	✓	✓	✓			✓							

Table 3
Comparing 4IR tech. to each category.

4IR Technology	Safety Asset Management	Building Energy Efficiency	Building Lifecycle Monitoring	Lifecycle Sustainability Assessment	Predictive Building Maintenance	Smart Building Asset Management	Stakeholder	Structural Health Monitoring
DT	5	9	19	4	8	14	4	15
BIM	7	9	19	5	9	17	6	14
IoT	6	7	17	4	7	16	3	15
AI	5	3	10	4	4	6	3	9
AR	3	1	6	0	3	3	1	4
GIS	2	2	8	2	0	3	2	4

Table 4
Strengths and Limitations of area application (Smart Building Asset Management).

Categories	Strengths	Limitations
Smart Building Asset Management	-Reliable asset management data collection [46]. -Accurate 3D models and improved collaboration with BIM [47]. -Continuous monitoring and improved decision-making processes [49]. -Real-time updating and interaction with building data [70]. -Enhanced data collection with IoT integration [71]. -Improved asset performance assessment using GIS and BIM [72]. -Smart management of HVAC systems and predictive maintenance [41].	-Challenges in field verification of asset data [46]. -Integration issues with existing BIM systems [47]. -Dependency on specific software tools and databases [49]. -Overwhelming BIM model with large file sizes [70]. -High initial investment and training requirements [41].

management systems, and external feeds, raising risks around unauthorised access to sensitive information. Implementing strong encryption, secure access controls, and adopting blockchain for immutable data storage are potential solutions to address these concerns [75,76].

Notably, DT and IoT devices can be used in Smart Building Asset Management (SBAM) to help improve the durability and efficiency of their assets. DT can refine management efficiency, and this was also revealed by (Lu et al., 2020) [41], how these technologies can help improve construction quality and efficiency, thus allowing continuous monitoring of building assets and anomaly detection, as well as integrating with industry standards such as Foundation Classes (IFC) to improve interoperability and data management. For instance, a "Live BIM" approach integrates real-time sensor data from HVAC systems into BIM models, enabling facility managers to monitor performance and schedule maintenance before failures occur proactively. This reduces downtime, improves energy efficiency, and enhances occupant comfort, as highlighted in recent studies [77,78]. This section has shown how Digital Twins significantly enhance smart building asset management by continuously monitoring and improving decision-making. However, to fully leverage its potential, high initial costs and integration challenges must be addressed.

4.2. Digital Twin for Predictive Building Maintenance

DT can help predict the maintenance needs of a building by integrating data collected from sensors and building models. This proactive approach can extend the lifespan of the building and reduce downtime [41,42,43,44]. This proactive approach can extend the lifespan of the building and reduce downtime. Studies by Coupry et al. (2021) [79] and Pan and Zhang (2021) [80] also demonstrated the limitations and strengths in Table 5 and provided an overview of digital technologies such as DT, BIM, and extended reality (XR) devices in the fields of building and facility management, especially DT.

Using technology such as DT in construction processes can significantly improve the quality and efficiency of the work performed in the field. It can also help reduce the time required to acquire and manage permits. In addition, within the context of the Fourth Industrial Revolution, it can provide a complete view of an asset's condition, allowing for predictive maintenance. BIM and 4IR technologies can significantly enhance the efficiency of construction processes, especially asset maintenance.

Table 5
Strengths and Limitations in the area of application (Predictive Building Maintenance).

Categories	Strengths	Limitations
Predictive Building Maintenance	-Enhanced real-time data access and predictive maintenance [79]. -Streamlined facility management and stakeholder collaboration [81]. -Improved maintenance planning accuracy using BIM [82]. -Comprehensive asset monitoring with DT [41]. -Proactive safety management with AI [80].	-Data quality, privacy, and interoperability challenges [79]. -High initial investment and varying effectiveness across buildings [81]. -Potential loss of information for old buildings [82]. -Significant resource requirements for system implementation [41]. -High computational costs and lack of accuracy in complex problems [80].

For example, two Digital Twin prototypes were developed by Asare et al. (2024) [83] to improve the predictive maintenance of air handling units (AHUs) in an academic building in the Southeast U.S.A. The first prototype, the "Buy" approach, utilised Autodesk Tandem to integrate sensor data with BIM-based visualisations. This allowed for real-time analytics and predictive maintenance by enabling facility managers to monitor the AHUs' conditions and proactively plan maintenance activities. The second prototype, the "Build" approach, combined Unreal Engine and Microsoft Azure to create a customised solution with dynamic visualisations and telemetry integration. This prototype emphasised enhanced anomaly detection and tailored predictive maintenance strategies. Both prototypes demonstrated the practical applications of DT in facility management, highlighting the value of real-time data integration and its potential to reduce downtime, optimise maintenance resources, and ensure operational efficiency [83]. In addition, a case study was done by Hosamo et al. (2022) for the I4Helse building at the University of Agder, Norway, showcasing a Digital Twin predictive maintenance framework applied to four Air Handling Units (AHUs). Real-time data collected from IoT sensors, such as temperature, pressure, and flow rates, were integrated into BIM models for analysis between August 2019 and August 2021. Using expert rules based on the APAR method, faults like simultaneous heating and cooling and unexpected heating were detected. Machine learning algorithms, including ANN, SVM, and decision trees, were used for condition prediction, with ANN achieving a 99.7 % accuracy rate. This framework enabled dynamic maintenance planning, allowing facility managers to prepare equipment and tools proactively, resulting in energy savings and extended equipment lifespan [84]. Moreover, XR and BIM-based DT can improve maintenance accuracy by overlaying data on the maintenance personnel's field of vision. With BIM technology, construction managers can improve facility management efficiency by creating and storing asset management in a digital format [42]. This technology can also help them streamline their operations by allowing them to access and share information about their properties. One example is the Hadrianeum in Rome, which was equipped with a digital asset replica to improve the building's maintenance [81]. Modern DTs are used in construction to automate the various tasks associated with asset management, which is vital for ensuring the durability and effectiveness of a facility's building components. In 2021, Huong et al. [42] suggested that various technologies, such as RFID, sensors, and barcodes, can be integrated into BIM to simplify data updates and asset identification operations.

These technologies support predicting and preventing breakdowns by analysing historical and sensor data. However, challenges remain concerning data privacy and data quality, which must be addressed to ensure successful implementation. For instance, there are no end-to-end solutions for creating digital twin predictive maintenance models. Often, the predictive maintenance system is developed on a separate platform from the digital twin, leading to imperfect integration when run simultaneously [85,86]. The integration of 4IR technologies can significantly reduce labour expenses and improve the efficiency of a facility's maintenance operations. However, implementing these technologies can be expensive and require training and equipment upgrades. In addition, continuous research is also needed to improve data management skills in BIM [42]. Notably, predictive maintenance can be established as a foundation to improve the efficiency of a facility's operations by utilising DT. From an economic standpoint, DT technologies can offer tremendous cost savings.

4.3. Digital Twin for building energy efficiency

DT has the tendency to accelerate building energy efficiency by analysing and monitoring a building's energy consumption. This data-driven approach aids in identifying inefficiencies and implementing strategies aimed at improving a facility's overall performance and lower energy consumption [50,51,52]. Table 6 examines the limitations and strengths in the application area as well as building energy efficiency. It also shows various digital technologies, such as DT, BIM, and Artificial intelligence (AI), that enhance building management and infrastructure, especially DT.

The implementation of DT technologies in the construction sector has substantially increased efficiency and control. Smart sensors and building information management systems can monitor and control a construction site's operations [44,88–91,52]. In construction works, DT uses sensors to continuously monitor a building's energy consumption, helping to reduce carbon emissions and improve the facility's quality [44,52] Through the use of Heritage Building Information Modelling (HBIM) and BIM, DT can provide a comprehensive view of a building's energy consumption and perform accurate simulation and modelling, improving sustainability and lifecycle monitoring [92] Additionally, integrating IoT sensors into DT enables real-time energy monitoring, reducing carbon emissions and improving energy efficiency [93,94]. According to Delval et al. (2024) [52], this technology can also be used to perform accurate monitoring without the need for regular inspections. For example, the Edge's Digital Twin integrates data from over 28,000 sensors monitoring temperature, humidity, occupancy, lighting, and more. This data feeds into a cloud-based platform, creating a digital replica of the building's systems, including HVAC, lighting, and energy consumption. The building achieved a 50 % reduction in energy use compared to traditional offices, showcasing the benefits of real-time monitoring and predictive analytics [95]. Another,

Table 6
Strengths and Limitations in the area of application (Building Energy Efficiency).

Categories	Strengths	Limitations
Building Energy Efficiency	-Improved sustainability and management through renewable energy integration [87]. -Enhanced maintenance and comfort with DT and BIM [50]. -Real-time energy assessment and predictive accuracy [88]. -Collaboration support and early performance analysis with BIM [89].	-Estimating carbon footprints and intervention costs [87]. -Challenges in integrating into diverse practices [44]. -High costs and data quality requirements [88]. -Technical constraints and setup costs [89].

according to Yu et al. (2023) [96] to their discussion about how digital twin (DT) technology can significantly improve efficiency in port areas, mainly through the integration and optimisation of renewable energy systems. It highlights that new energy power generation, such as renewable energy, is crucial for the low-carbon operation of ports. Also, Yu et al. (2023) [96] mentioned that the digital twin can provide more complete operation simulation capabilities, support interaction with various real factors, and gather operating experience to make performance evaluations more objective and accurate. This demonstrates the diverse applications of DT for enhancing energy efficiency in port areas.This category shows how Digital Twins enhances building energy efficiency by enabling real-time monitoring and predictive analytics, but high costs and integration challenges must be overcome for effective deployment.

4.4. Digital Twin for structural health monitoring (SHM)

Structural Health Monitoring (SHM) can be carried out through DT by integrating sensor data. This method can help identify potential structural issues before causing problems that could endanger the occupants or the building itself [60,61,62,63]. They also noted with other researchers the limitations, strengths in Table 7 and constraints of 4IR technologies in the AEC sector in their studies, which showcased its ability to improve monitoring, accuracy, and management across construction projects using innovative DT, VR, and AI techniques, and helped decrease maintenance expenses and enhance project schedules. For example, the water distribution network in Valencia, Spain, demonstrates the application of Digital Twin technology beyond structural health monitoring. The DT models 113,000 pipes, 8 reservoirs, 28 tanks, and other components, enabling anomaly detection, demand forecasting, emergency planning, maintenance scheduling, and operational optimisation. Updated every minute, the DT provides insights into long-term network behaviour and emergency scenarios [97].

Integrating DT technology in Structural Health Monitoring (SHM) in asset management (AM) has proven the system can utilise a combination of sensors, computational models, and data analytics to provide continuous and accurate monitoring of various SHM conditions. The system also allows for continuous structural compliance checking and facilitates perpetual permitting processes. Various studies have been conducted by different researchers, including [102,103,104,62,63]. Their studies showed that SHM uses advanced sensors and data analytics to detect structural issues such as corrosion and cracks, which can be costly and safety threats. Through its integration with DT technology, SHM can provide a virtual replica of a structure, eliminating the need for physical inspections, a significant improvement over traditional methods. According to the studies conducted by Refs. [99,105,61], integrating DT with other building processes can help improve the efficiency and effectiveness of a building's construction and regulation compliance [99,105].

Notably, digital twins for Structural Health Monitoring (SHM) represent a transformative approach to monitoring, maintaining, and improving the integrity of civil infrastructure. However, their implementation comes with challenges, primarily high costs and complexity. This is because developing a high-fidelity DT requires advanced sensors, IoT devices, and computational infrastructure, which can be expensive [106]. Tailoring DTs to unique structures increases costs due to the need for bespoke designs and integration efforts. In order to address this challenge, starting with pilot projects is advisable and thereafter focusing on the critical components, and then scaling up slowly. Integrating existing SHM systems into DTs where possible is recommended to reduce duplication of costs as well as cloud computing adoption of data storage and analytics to reduce the need for expensive on-premises infrastructure [107]. In another study, Sakr and Sadhu (2023) [63] analysed BIM-IoT civil engineering SHM integration, which monitors and displays the structural responses of a building using various IoT sensors, Arduino microprocessors and MySQL databases, which process data and update the BIM in real time. Its colour-coded visualisations of structural changes to identify potential repairs and maintenance issues. changes to identify potential repairs and maintenance issues. A case study was conducted in 2022 by Egodawela et al. (2023) [60] to evaluate the Digital Twin framework's initial steps in Sri Lanka's Polonnaruwa. The research utilised a comprehensive methodology involving 3D reality modelling, a photogrammetry survey, and archaeological analysis. The study led to the creation of a rich HBIM model that focused on the main structure of the Buddha's shrine, which is located at an elevation of over 75 m. It analysed the site's other cultural and archaeological features, such as stone seating and Wahalkadas. The case study's findings support the use of DT technology to validate its effectiveness.

Regarding complexity challenges, combining diverse sensor systems, legacy monitoring tools, and predictive analytics into a unified platform is complex, and the continuous influx of high-resolution data creates challenges in processing, storing, and extracting actionable insights. Also, ensuring that the DT accurately represents the physical structure and evolves with it over time requires sophisticated algorithms and calibration. Addressing these challenges involves developing and adopting industry-wide standards for data collection, processing, and integration [108]. Utilising AI to process large datasets efficiently, detect anomalies, and predict failures. For example, the Rędziński Bridge in Poland utilises a Digital Twin to monitor its status as the largest cable-stayed bridge in

Table 7
Strengths and Limitations in the area of application (Structural Health Monitoring (SHM)).

Categories	Strengths	Limitations
Structural Health Monitoring (SHM)	-Improved monitoring precision and early damage detection [61]. -Efficient 3D data capture with drone photogrammetry [60]. -Enhanced visibility and reliability in construction processes [98]. -Real-time monitoring and control with DT [99]. -Cost savings and streamlined project timelines [100].	-Integration difficulties with existing systems [101]. -Complexity and operational issues [61]. -High initial investment and training requirements [100].

the country. The system integrates real-time data from 222 sensors measuring tension, displacement, and temperature. However, the project faced challenges related to high initial costs and the complexity of integrating a large number of sensors [109]. To address these issues, a phased implementation approach was adopted, focusing initially on high-risk sections. Additionally, AI was deployed to prioritise and optimise sensor data analysis, ensuring efficient resource utilisation [110].

More so, a study by Hunhevicz et al., 2022 [103] revealed that a performance-based asset management system using blockchain technology and digital twin models could improve the efficiency and effectiveness of a building's construction. Notably, one of the most critical factors architects and developers need to consider when implementing DT technology is integrating data between the "back-end" and "front-end" oracles. Despite the technological advancements in the field, implementing DT technologies remains a challenge [103,62]. For instance, training and technology are necessary to monitor and improve the performance of a building's physical assets. According to Teisserenc and Sepasgozar (2021) [104], blockchain technology (BC) can help improve the security and efficiency of DT in the construction industry by allowing them to maintain and collect records in a tamper-proof manner. This category shows how Digital Twins enhances structural health monitoring by providing precise, real-time data to enable early issue detection. However, addressing high costs and integration complexities is necessary for broader adoption.

To ensure the successful adoption of complex DT systems, organisations are encouraged to increase the digital maturity of their workforce. Building a digitally skilled team allows for smoother implementation and effective use of advanced DT tools in SHM and other areas [97].However, Future research could explore developing open-source tools to reduce the initial costs of Digital Twin implementation and create standardised training programs to support the adoption [111].

This category shows how Digital Twins enhances structural health monitoring by providing precise, real-time data to enable early issue detection. However, addressing high costs and integration complexities is necessary for broader adoption.

4.5. Digital Twin for lifecycle sustainability assessment (LCSA)

DTs for lifecycle assessment enable a comprehensive view of a facility's various phases, such as construction, demolition, and operation. This helps identify areas for improvement and promotes sustainable practices [53–55]. Their studies with other scholars also show the strengths and limitations in Table 8 of OPW ontology, BIM, and DT technologies in building and manufacturing from the articles selected with the main Lifecycle Sustainability Assessment application. BIM and DT improve data integration for LCSA in buildings; however, data quality and availability are essential. DT technology in construction increases governance and management by connecting physical and digital assets, but it has significant implementation costs and extensive data management requirements. BIM improves visualisation and information management. For instance, Ukraine's incomplete building rehabilitation is an example for a lifecycle sustainability assessment, according to a study by Lukianova et al. (2020) [112].

Lifecycle Sustainability Assessment (LCSA) evaluates buildings' environmental, social, and economic implications during their lifecycle. This approach integrates three primary assessments: Environmental Life Cycle Assessment (E-LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA), which examine environmental, economic, and social aspects in this comprehensive approach [53]. In these articles [53,54,113], and [55] discuss the different approaches to evaluating and improving building efficiency using DT. In addition [55], highlights the capacity of DT technology to enhance the management of building lifecycles by integrating with big data and IoT, especially during the operation and maintenance (O&M) stages. Notably, Digital Twins supports lifecycle sustainability assessments by offering real-time data to promote sustainable practices. These practices ensure that managing implementation complexity is essential for success. Besides, this integration enhances the management of building lifecycles and assessment accuracy and improves decision-making during critical phases such as reconstruction. Incorporating Digital Twins (DTs) into LCSA frameworks makes continuous real-time data on infrastructure performance, material degradation, and operational efficiency accessible. Additionally, DTs enable dynamic updates to LCSA models by reflecting the current state of infrastructure and projecting future scenarios using predictive analytics [114]. For example, during the construction of the Mohammed VI Bridge in Morocco, Digital Twin (DT) technology was employed to monitor and maintain the infrastructure. The DT enabled the integration of mobile mapping and machine learning to assess the bridge's condition and predict maintenance needs [115]. This approach allowed for real-time data collection and analysis, ensuring the bridge's structural integrity and optimising maintenance schedules to prevent potential issues; monitoring throughout the construction process ensured compliance with sustainability goals.

4.6. Digital Twin for building lifecycle monitoring: context of building and construction

A building's lifecycle monitoring system ensures continuous evaluation of its efficiency and helps identify improvement areas from

Table 8
Strengths and Limitations in the area of application (Lifecycle Sustainability Assessment).

Categories	Strengths	Limitations
Lifecycle Sustainability Assessment (LCSA)	-Enhanced data integration and completeness with BIM and DT [53]. -Real-time evaluation and control of sustainability criteria [113]. -Improved efficiency and decision-making in reconstruction projects [112].	-Data availability and accuracy issues [53]. -Complexity in adapting to varied project states [112]. -Challenges in managing sustainability information [113].

inception to decommissioning throughout its entire lifecycle [57], which supports our aim of continuous permitting and compliance checking. Furthermore, DT offers a way to monitor a building's lifecycle continuously. This method can help improve efficiency and safety [56,57,58,59].

Studies of the likes of [116,117,58] show the strengths and limitations of selected articles with other researchers in Table 9, as well as investigate the increasing number of DT and BIM in various frameworks that have highlighted the advancements in facility and construction management. These technologies are helping to improve the efficiency of the process by allowing users to visualise and analyse data. Nonetheless, DTs and BIM face numerous technical and financial barriers. These include the complexities of data integration, security and operational concerns, and the lack of standardisation and research. Despite these barriers, their potential to transform construction is still in the early stage, and their optimisation and adoption need to be carefully planned and executed. Moreover, Digital Twins (DTs) have the potential to enhance productivity, resource efficiency, health, and safety in construction environments by enabling continuous monitoring and analysis of various parameters during construction – continuously tracking structural performance and operational parameters, DTs can automatically compare them to regulatory standards and simulate various scenarios, proactively identifying potential compliance issues before they arise [118]. However, sensor degradation, accuracy drift, and environmental interference can affect data quality. These issues can be addressed by installing multiple sensors to enable cross-verification and leveraging machine learning models within the DT to detect and compensate for inaccuracies in real-time. Similarly, data input challenges, such as incomplete or inconsistent data, can lead to inaccurate modelling. Integrating data from diverse sources such as IoT devices, legacy systems, and satellite imagery and pre-processing this data within the DT to flag and correct inconsistencies can ensure reliable and comprehensive input for accurate assessments [119].

DT technology in civil engineering improves operational management and asset value, especially in building lifecycle monitoring (BLM). Jiang et al. (2021) [99] stresses the need for DT definitions and applications in civil engineering to connect it with BIM and CPS. Huynh and Nguyen-Ky (2020) [56] proposes an interoperable visualisation of a building's DT to enhance operational performance using real-time data and occupant input in facility management. Almukhtar et al. (2021) [47] discuss the issues of integrating laser scanning data with BIM settings and using 3D laser scanners to create realistic as-built models. These studies demonstrate the advantages of DT, BIM, and 3D laser scanning in civil engineering and BLM, including operational efficiency and proactive asset management, while recognising data quality and technological integration issues. A study conducted in a Chinese hospital by Peng et al. (2020) [57], revealed that the use of DT technology could help improve the efficiency of the facility's building operations.

By connecting various systems, such as a static BIM system, the data could be analysed and disseminated in real-time. The study also utilised a combination of dynamic and static data collected throughout the facility's construction and design. Notably, Digital Twins enhances building lifecycle monitoring by providing continuous, real-time data. However, overcoming data and integration challenges is essential for effective implementation.

4.7. Digital Twin for asset safety management

DT can help improve the management of safety assets by providing relevant data to stakeholders in real-time, allowing for prompt interventions to minimise risks [64,65]. In their studies, they show with other scholars the strengths and limitations in Table 10 based on Safety asset management from the articles selected in this research, resulting in the various studies that have examined the integration of different building technologies to improve safety management, monitoring, and decision-making. Consolidating such technologies is vital to creating smart buildings that can effectively address real-world challenges.

Nevertheless, it is essential to keep in mind that despite these studies' progress, their applications are often limited and tailored to specific projects.In addition, a study conducted by Liu et al. (2020) [65] explores the utilisation of DT in managing indoor safety. To improve safety management, they have developed a DT model (DTM) to collect and analyse data from various sensors and support vector machines (SVMs) to enhance building safety management, which can then be used to improve the intelligence in the systems that monitor and manage safety. In addition [65], created an integrated safety management system (ISMS) framework that uses IoT and BIM to establish a DTM for building safety. This method can be used to monitor and improve the status of the building's operations. By using IoT sensors, the team can collect real-time data about the building's safety. The SVM is an algorithm that can automatically identify and assess hazards in an indoor environment. In 2020 also, Liu et al. [65] presented a framework that uses DT technology to improve safety management in a building. The framework was used to analyse data collected for the 2022 Winter Olympics in Beijing. Notably, Digital Twins enhances safety asset management by enabling real-time risk monitoring and decision-making. However, challenges such as data verification and lack of standard protocols.

Table 9
Strengths and Limitations in the area of application (Building Lifecycle Monitoring).

Categories	Strengths	Limitations
Building Lifecycle Monitoring	-Enhanced project oversight and accuracy with real-time data [58]. -Improved safety and emergency management with BIM [120]. -Efficient development of interoperable building visualisations [56]. -Comprehensive monitoring and analysis for construction safety [59]. -Improved productivity and reliability with DT [99].	-Need for substantial data inputs and integration complexity [58]. -Limited machine learning capabilities [120]. -Limited availability of BIM models for older buildings [56]. -Dependence on sensor performance [59].

Table 10
Strengths and Limitations in the area of application (Safety Asset Management).

Categories	Strengths	Limitations
Safety Asset Management	-Reliable asset management data collection [46]. -Enhanced data collection and decision-making with IoT, AI, and BIM [64]. -Efficient checking and balancing of building bylaws and regulations [121]. -Accurate danger classification and level assessment [65]. -Improved visualisation and collaborative decision-making with AR and VR [122].	-Challenges in field verification of asset data [46]. -Lack of standardised protocols and interoperability [64]. -Limited applicability of mobile applications to specific regions [121]. -Generalizability issues in specific case studies [65]. -Lack of comprehensive analysis and adoption challenges [122].

4.8. *Digital Twin for stakeholder management: collaboration, transparency, and sharing*

One of the technological tools that enables stakeholders to achieve real-time project data and collaboration improvement is called digital twin [66,67]. But according to Halmetoja 2022 [67], digital twins can also expose projects to cybersecurity risks in addition to its costly implementation. DT helps improve the efficiency of stakeholder management by providing relevant and timely information to all concerned parties. It also fosters better collaboration and communication among those involved [123,66,67].In Table 11, the authors pose limitations and strengths of the articles using DT and BIM to manage construction projects. Some of the advantages include better transparency and collaboration among stakeholders, but it also comes with challenges like cybersecurity risks and implementation costs. Even though tools such as the BIM-FM facility can help improve operations, it requires more accurate information. In one of the articles, Hosamo et al. [123] argue that scientometric analysis is not practical enough, as it only focuses on theoretical understanding.

However, Silva et al. [126] found that using UAVs and photogrammetry in BIM is beneficial for heritage building documentation, but it depends on the data's freshness and accuracy. Although a web app for collaborative IFC document editing is proposed to promote open-source access, it does not provide a comprehensive technical description. This is why it is essential that the developers thoroughly implement this technology and resolve these issues.

It must be mentioned that DT plays a notable role in asset decision-making throughout its lifecycle as it helps to refine stakeholder management and develop effective decision-making strategies. Nonetheless, an inclusive approach to planning and implementing smart cities is also needed to balance the environmental and economic impact [123]. Over the years, DT has helped building owners and managers to realise a deeper understanding of their facility, thereby giving them more informed decisions and improving their engagement with stakeholders [67]. Future research could focus on evaluating the long-term economic impacts of Digital Twins on asset management, including cost reductions in permitting processes and improved return on investment through enhanced collaboration and efficiency. Additionally, exploring how Digital Twins can integrate into existing regulatory frameworks would enhance their practicality in the construction sector. This aligns with the need for a comprehensive and quantitative maturity model for Digital Twin implementations, as Chen et al. (2021) discussed in their development of a Gemini Principles-Based Digital Twin Maturity Model for Asset Management [127], which helps stakeholders by providing a systematic and quantitative method to evaluate and improve the implementation of digital twins for asset management. This technology also helps improve the efficiency of construction processes, which is particularly evident in construction permitting and compliance checking. Therefore, integrating BIM can help improve stakeholder management in smart buildings as It provides adequate support to ACE sectors to work together effectively by allowing them to resolve design conflicts before starting construction [125]. Notably, Digital Twins improves stakeholder management by enhancing transparency and collaboration. However, managing cybersecurity risks and high costs is crucial for implementation.

These findings demonstrate that Digital Twins have significantly advanced construction asset management by enabling real-time data visualisation, predictive analytics, and enhanced collaboration. Key achievements include integrating IoT and AI for predictive maintenance, which has reduced downtime and operational costs, as well as promoting sustainability through real-time lifecycle assessments. Table 1 summarises these advancements across various thematic areas, highlighting their transformative potential in optimising permitting and compliance processes within the construction industry. However, data interoperability, scalability, and cybersecurity remain significant barriers to widespread adoption. Addressing these limitations is essential to fully realise the potential

Table 11
Strengths and Limitations in the area of application (Stakeholder Management).

Categories	Strengths	Limitations
Stakeholder Management	-Improved project information transparency and stakeholder collaboration with DT [66]. -Efficient facility operations and maintenance support with BIM-FM [124]. -Enhanced maintenance and troubleshooting with DT [67]. -Better understanding and collaboration with scientometric analysis [123]. -Comprehensive "As Built Drawings" with UAV and photogrammetry data [125].	-Significant implementation costs [66]. -Need for improved standardisation in information management [124]. -Cybersecurity concerns [67]. -Exclusion of practical and commercial innovations [123]. -Dependence on data accuracy and synchronisation [125].

of Digital Twins in revolutionising construction practices. So, Table 12 summarises the key achievements and examples discussed in Sections 4.1 to 4.8, offering a consolidated overview of progress in the field.

5. Conclusion

This study systematically reviewed the progression and application of Digital Twin (DT) technologies within the construction industry, focusing on asset management and continuous permitting and compliance checking. The study revealed a total number of 80 review research articles on application and integration of DT technologies within the construction industry especially in asset management. It demonstrated how these technologies when integrated with other innovations such as the IoT and AI, have transformed the way construction practices are conducted. As a result, Implementing DT technologies can help boost productivity and minimise operational interruptions in the construction industry. The study showed its support for both the goals of the Fourth Industrial Revolution and the economy by improving asset management.

Additionally, this study's findings highlight the need for continued research on using DT in the construction industry to improve the efficiency of permitting and compliance checking. Although the research on permitting and compliance checking is limited, the available evidence suggests that DT has the potential to streamline and monitor these processes. However, construction firms and governments as municipalities can automate and streamline their permitting processes and ensure that all project requirements are met at every step of the project's life cycle by implementing DT, which is thus capable of enhancing and maximising knowledge between organisations. This can significantly improve the quality and efficiency of their operations. DT can help prevent potential issues by predicting before they happen by using data collected by sensors and other sources, and this attribute eliminates the need for traditional methods in the context of the construction industry.

Despite DT technologies' numerous advantages, several challenges prevent organisations from fully utilising its potential. These include the complexity of data management and the interoperability of their systems. To maximise its potential and encourage its widespread adoption, conducting studies and further research on the economic impact of this innovation must be consistent. Notably, this study's outcomes also revealed that a growing number of studies focus on using DT in construction projects, such as smart and safety asset management, structural health monitoring, stakeholder management, building lifecycle monitoring, energy and efficiency, and assessment lifecycle sustainability. These studies are expected to help develop new ways of improving construction, especially in monitoring and predicting issues that appear on the site. While DT technologies present considerable opportunities to improve the quality and efficiency of construction projects and asset management, they are still not feasible for the entire construction industry. In order to realise its full potential, it is advised to overcome existing issues and expand the scope of research to encompass all aspects of the application areas. The systematic review approach used in the study answers the key research questions, demonstrating that DT technologies significantly improve efficiency and quality in construction processes compared to traditional methods; we can answer our research question.

5.1. Do digital twin technologies significantly improve efficiency and quality in construction processes over traditional methods, especially in construction permitting and compliance?

To answer this, we have found out in the discussion section that digital twin technologies can significantly improve efficiency and quality in construction processes compared to traditional methods, which can be compared to the traditional by using digital twin for continuous permitting and compliance checking. These tools provide a variety of features and capabilities, such as real-time data and predictive maintenance. They help organisations comply with technical standards and reduce the need for regular physical inspections. DTs can help improve the efficiency and quality of construction by facilitating more accurate updates and making decision-making processes more effective.

Table 12
Key achievements and examples in digital Twin applications.

Category	Key Achievements	Example
Smart Asset Management	Enhanced decision-making with real-time data integration.	Live BIM'' integrates sensor data with BIM models to monitor HVAC performance, enabling proactive maintenance and improved energy efficiency [77].
Predictive Maintenance	Reduced maintenance costs and downtime through real-time monitoring.	The I4Helse building in Norway uses DTs to predict and prevent maintenance issues, minimising disruptions [84].
Building Energy Efficiency	Significant energy consumption reduction via predictive analytics.	The Edge building in Amsterdam reduced energy consumption by 50 % using a DT system with 28,000 sensors [95].
Structural Health Monitoring (SHM)	Real-time anomaly detection for improved safety.	Rędziński Bridge in Poland monitors structural conditions with 222 sensors, enhancing safety despite high integration costs [109].
Lifecycle Sustainability Assessment (LCSA)	Sustainability metrics monitored during construction.	Mohammed VI Bridge in Morocco uses DTs for condition monitoring and predictive maintenance, ensuring long-term sustainability [115].
Building Lifecycle Monitoring	Continuous lifecycle data integration for optimisation.	A Chinese hospital improved operational efficiency by integrating static and dynamic data with DTs [57].
Safety Asset Management	Improved safety compliance through IoT integration.	A DT model integrates IoT sensors and machine learning to improve building safety and compliance [65].
Stakeholder Management	Enhanced collaboration with DT platforms.	Gemini Principles-based DT models promote stakeholder transparency and teamwork in asset management [127].

5.2. Considering their implications for economic growth, how do these technologies integrate into asset management within the context of the fourth industrial revolution?

To answer this, we have found out in the discussion section that digital twin technologies can integrate seamlessly into asset management within the context of the Fourth Industrial Revolution by leveraging advancements in AI, IoT, AR, and GIS. This integration can enhance efficiency, precision, and operational control, significantly benefiting the economy. These technologies can help improve the efficiency and longevity of an asset by providing predictive maintenance and monitoring its real-time condition. The construction industry can grow by capitalising on the integration of DTs. This can facilitate data-driven decision-making and foster innovation, which benefits the industry's economic growth.

5.3. What are the future research needs and goals for further developing and implementing digital twin technologies in construction, especially in asset management?

In future research, researchers should prioritise the development of digital twin technologies. Various challenges, such as cybersecurity and data integration, need to be resolved. Interoperability and standardisation of data protocols are essential for seamless collaboration and integration between DT platforms. Additionally, there is an urgent need to explore the feasibility of implementing digital twin technologies in construction projects. To address this, investigate intellectual capital's role in optimising asset management techniques. There is a lack of comprehensive reviews regarding the proper utilisation of intellectual capital and knowledge management in the article for implementing DT, where intellectual capital can be harnessed to improve asset management efficiency. It also shows that digital technologies can only perform well if focused on the most beneficial portion of intellectual capital. Although knowledge management is primarily focused on managing organisational knowledge, incorporating intellectual capital can help improve the implementation and development of DTs. The various elements of intellectual capital, structural, human, and relational, give rise to a unique framework that enables the smooth implementation of projects, which is a powerful tool that can be utilised for development and implementation.

Future research should evaluate the lifecycle costs and benefits of Digital Twins (DTs) in asset management, including savings from reduced maintenance, efficiency gains, and extended lifespans while aligning DTs with international standards for global adoption. Quantifying the long-term economic benefits, such as the potential for reducing operational costs by up to 20 % or extending asset lifespans by approximately 15 %, could help establish the business case for broader DT adoption in construction. Integrating Fourth Industrial Revolution (4IR) technologies such as Artificial Intelligence (AI) and Blockchain can optimise performance, enhance predictive analytics, and improve data security, boosting transparency and efficiency in smart infrastructure. Key priorities include developing standardised protocols for data formats and communication interfaces to integrate DTs into regulatory frameworks and streamlining compliance through automated reporting, real-time monitoring, and scenario simulations. Addressing data privacy, security, and ownership challenges will be critical for their successful implementation and adoption. Conclusively, policymakers and scholars can use this study's findings to develop regulations and improve construction efficiency. Policymakers should consider developing global regulatory standards to harmonise the adoption of DT technologies, including protocols for data privacy and interoperability. Establishing a framework for integrating DTs with existing building codes and ISO standards could streamline regulatory compliance and enhance the global adoption of this technology. Implementing DT technologies can also help improve project outcomes. Moreover, incorporating Digital Twin technology into the asset management processes offers a promising path toward achieving efficiencies and innovations.

CRediT authorship contribution statement

Alsaffar Alhadi: Writing – original draft. **Beach Dr Tom:** Supervision. **Rezgui Yacine:** Supervision.

3. Findings

The 80 articles selected for the study were subject to a systematic analysis. Several studies have been conducted on using DT to

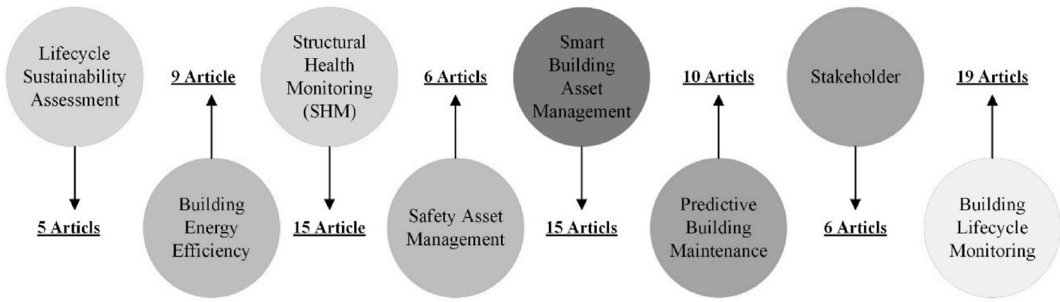

Fig. 3. Categories with article numbers.

improve asset management. Most articles analysed the proposed framework for implementing DT in construction. However, the studies selected for this review focused on gathering information about the building process to improve its efficiency. These studies were categorised into 8 categories using the PICO framework, as shown in Fig. 3, which also shows the number of articles in each category. The systematic review highlighted the significant potential of digital twin technologies to transform asset management and construction processes.

According to the Web of Science database, the table inside Fig. 4 demonstrates the top 10 countries ranked by the number of research records. The USA is leading the list. This could indicate research activity and funding presence in each country's field. Moreover, the diversity of countries on the list suggests a global interest in the field, contributing to the collective knowledge base.

Additionally, Fig. 5 *displays the number of document journals published in Digital Twin research results from the Scopus database, where publications from 2020 are published, along with the modified projections for the end of 2024 based on 21 March 2024 publications.*

Different categories of articles focused on implementing digital twins in the construction process. These included predictive maintenance, stakeholder management, smart asset management, building energy efficiency and sustainability assessment, life cycle monitoring, and structural health monitoring. It was discovered that most studies on creating a digital twin focused on integrating various digital technologies, such as the Internet of Things, Artificial Intelligence, and Virtual Reality. Nonetheless, the gap literature review revealed that there was no study that focused on digital twin applications to improve the building's continuous permitting and compliance checking. Instead, they focused on using technology in construction.

Researchers can, however, use VOSviewer to support the process of systematic reviews, as about 80 publications were analysed using data collected from VOSviewer. This is because the VOSviewer software application is a powerful tool for constructing and visualising bibliometric networks. It helps in the current study by analysing trends and relationships within large datasets from academic databases. This data includes citation counts, keywords, publication titles, abstracts, authorship information, and publication years. The relevant articles were selected and exported into CSV files compatible with VOSviewer [128], which can support researchers to identify and visualise the distribution of publications across different topics or periods [129,130]. A software was developed to view publications based on abstracts from Table 2. Overall, 80 research papers were considered for analysis. In Fig. 6, 25 keywords were selected from 3292 total link strengths words and 3 clusters. The font size and node area visually represent the keyword's significance, determined by its frequency in collected abstracts. The figure highlights that the keywords (Digital Twin, BIM, Asset, IoT, Technology, and Management) carry substantial weight, indicating their prominence in the field, which provides a foundational understanding of how DT technologies intersect with compliance processes, offering guidance for future research.

Fig. 6 also shows the interconnected nodes and the relationships among various elements. For instance, the node representing "Digital Twin" is linked to "Challenge", "Research", and "Lot". This analysis aims to describe thematic distinctions among diverse clusters, an additional layer of understanding to stimulate discussion of findings to identify potential areas of interest, each characterised by its unique keywords. The first cluster predominantly pertains to "Assets", "BIM", "Building", and "Maintenance". The second cluster primarily focuses on "Digital Twin", "Technology", and "IoT", while the third cluster is characterised by "Engineering", "Construction", and "Architecture". A careful examination of the keywords associated with each cluster reveals a thematic interconnectedness within each cluster.

3.1. Connection between trends and research questions

The visual aids, including the geographic distribution of research output and the VOSviewer, provide valuable insights into global Digital Twin (DT) technology research trends. The map in Fig. 4 highlights regions as leading contributors to DT-related research, reflecting their prioritisation of advanced construction practices and regulatory frameworks. This aligns with the research questions, particularly those addressing the scalability of DT applications across jurisdictions with diverse regulatory environments. In addition, the VOSviewer in Fig. 6 showcases a keyword analysis, which directly correlates with the study's focus on continuous permitting and compliance checking. These clusters validate the research question concerning how DT technologies can optimise construction practices through real-time data and enhanced interoperability. By identifying the concentration of research and its thematic priorities, these trends underscore the global significance of the challenges this study aims to address.

This suggests that the information collected from the DT platform could be used to improve the building permit process. This also forms the knowledge gap in the literature, which the findings of this study will fill. However, this study's extensive review of the developed DT framework categorises and discusses extensively how the frameworks can enhance building continuous permitting and complaint in the construction industry and explore the various effects of digital technologies on the economy. It examines how they can be integrated into asset management during the fourth industrial revolution. Table 2 provides comprehensive information about the review findings. It presents the technologies in the context of the Fourth Industrial Revolution (4IR), such as (BIM, IoT, AI, AR, and GIS) used in the articles alongside or integrated with DT.

In the field of smart construction, various Fourth Industrial Revolution (4IR) technologies, especially DT and BIM and their integration with (IoT, AI, AR, and GIS) are employed to significantly enhance different aspects of building and asset management.

Table 3 is derived from the detailed analysis of the 80 articles selected in the systematic literature review in Table 2. These articles were categorised into different categories, and the frequency of specific 4IR technologies (DT, BIM, IoT, AI, AR, and GIS) mentioned in each category was counted based on each article, which highlights the technology's strengths and weaknesses. As shown in Table 3, The use of DTs has been regarded as the most effective platform for building lifecycle monitoring, scoring the highest "19", which means 19 articles mentioned and analysed DT. It performs well in structural health monitoring and predictive maintenance, which are vital in ensuring the building's integrity and proactive maintenance.

Nonetheless, DT exhibits limited capabilities when it comes to assessing lifecycle sustainability. BIM performs well in various

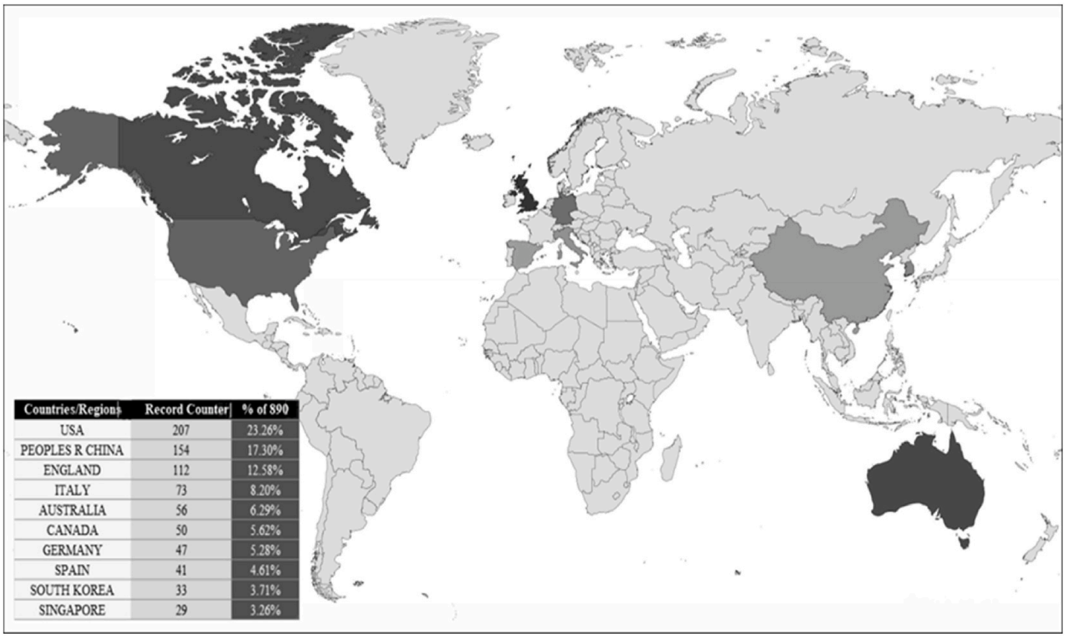

Fig. 4. MAP highlighting the top 10 countries for a Recorded count.

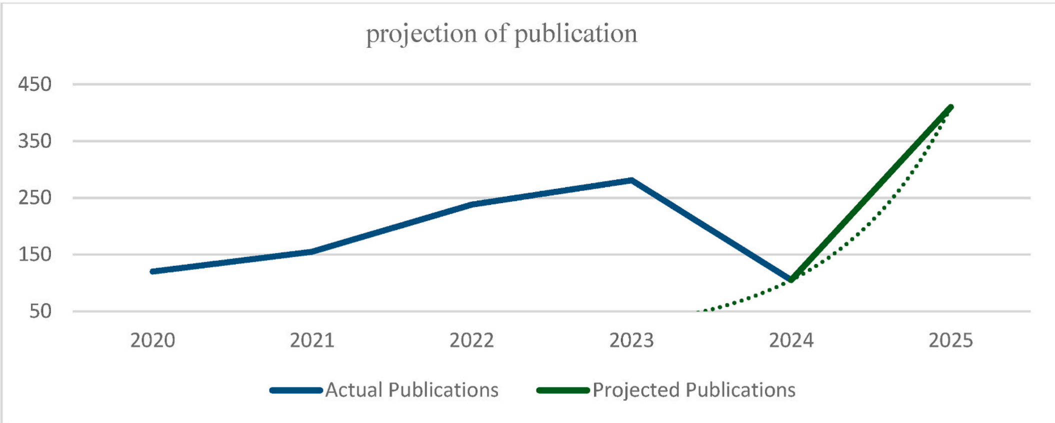

Fig. 5. Projection on 2024 based on the current date.

metrics, such as predictive maintenance and smart asset management. The Internet of Things is also an excellent platform for building lifecycles monitoring and structural health monitoring. Its ability to collect and analyse real-time data improves a building's energy efficiency.

Overall, the systematic review of articles revealed that the various applications of 4IR technologies were discussed in different contexts. For instance, Digital Twins were featured in several articles that focused on safety asset management which show the potential to improve the construction assets management. This study was divided into eight categories that tackled different aspects of smart construction. In addition, the study noted that these technologies can help maintain the integrity of buildings. However, the study's findings revealed a knowledge gap regarding using DTs in carrying out compliance checks and building permits. The study also highlighted the possibility of integrating different digital technologies into a framework for smart construction.

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.

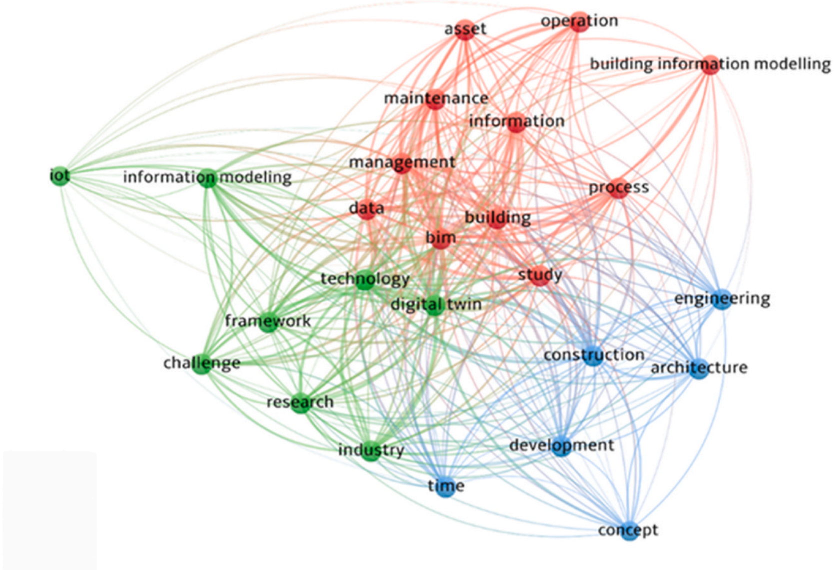

Fig. 6. Network in research, source (Author by VOSviewer).

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Data availability

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

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