# A SYSTEMATIC REVIEW OF DIGITAL TWIN AS A PREDICTIVE MAINTENANCE APPROACH FOR EXISTING BUILDINGS IN THE UK

***Modupe B. Sobowale***
*School of Natural and Built Environment, Department of Civil Engineering, Faculty of Engineering and Physical Sciences, Queens University Belfast*

***Dr Faris Elghaish & Dr Tara Brooks***
*School of Natural and Built Environment, Department of Civil Engineering, Faculty of Engineering and Physical Sciences, Queens University Belfast*

***ABSTRACT:*** *Digital Twin (DT) developments and applications in the Architectural Engineering Construction (AEC) Industry are emerging. However, insufficient publications synthesised the existing literature on DT of existing buildings, including energy retrofit and challenges as part of Net-zero strategies. When developing DT systems, it is vital to include the existing buildings primarily captured in 2-Dimensions (2-D) static data. To date, the implementation of DT has been minimal in applications in existing buildings in the UK. Despite DT benefits for maintenance (O&M) managers, facilities management (FM) as a comprehensive source of consistent data for predictive maintenance. This study explored the challenges faced by DT adoptions in existing buildings through a systematic review of the extant literature. A systematic approach is adopted to search the Scopus database using relevant keywords such as "Digital Twin.", "Built Environment" and "Existing Buildings.". the study focused on publications from the past five years (2018 to 2023) and prioritised articles in Scopus. The findings of this paper showed that the practitioners, O&M managers, and academics in built environments need more proper knowledge and technical expertise on digital twins as part of Industry 4.0 (I4.0). Evidence from the literature resulted in low empirical case studies and applications. The complexity of real-time data integration and interoperability were highlighted as part of the challenges despite the need for comprehensive knowledge of DT in the built environment. Scarce publication on the study was noted. The directions for comprehensive solutions and future research on digital twin applications in existing buildings towards achieving efficient energy retrofits, cost reductions, and net-zero goals were highlighted.*

***KEYWORDS:*** *Digital Twin, BIM, Data, Buildings, Energy, Management.*

## 1. INTRODUCTION

The emergence of Industry 4.0 has shifted the trajectory in the built environment. Digital Twin (DT) is essential to implement Building 4.0 (Delgado et al., 2023). There is more interest in DT technology as a building block of the metaverse and a vital pillar of Industrial 4.0 that needs to be harnessed (Hassani, Huang, & MacFeely, 2022). What is the place of DTs in constructed facilities projects? (Khallaf, Khallaf, Anumba, & Madubuike, 2022). The Digital Twin framework is based on Building Information Modelling (BIM) and a newly created plug-in to receive real-time sensor data from the physical instance (H. Hosamo, Hosamo, Nielsen, Svennevig, & Svidt, 2023). The built environment needs to move from a static sustainability assessment to a DT- based and IoT dynamic approach to turn climate and environmental challenges into opportunities and support the sustainability decision processes throughout the whole building's life cycle (Tagliabue et al., 2021). DT has become a 'hot topic' among academic circles and commercial communication in the industry. However, the DT is often misunderstood or misused as it is 'trendy'(Zhou, Zhang, & Gu, 2022).

Why DT instead of a traditional monitoring system? Traditional or human monitoring systems resulted in wastages, siloed documentation, and incorrect monitoring activities (Agrawal, Thiel, Jain, Singh, & Fischer, 2023; Khalil, Stravoravdis, & Backes, 2021; Sagarna, Otaduy, Mora, & Leon, 2022). Change is required, and DT could solve these problems better. The awareness of the interaction of humans and DT is vital to eliminate costs, strategic misalignments, misallocation of resources, and unrealistic expectations from DTs due to DT technology's immaturity (Agrawal et al., 2023).

DT is needed for prediction and stimulation due to the inability of the 2-Dimensioal (2D) or 3-Dimensional (3D)-BIM) data on its own to give a suitable platform for prediction. The local and global market dynamic changes require more robust and innovative operational BIMs in the AEC-FM sectors. The static 3D model needs an active approach (Harode, Thabet, Jamerson, & Dongre, 2023). However, the existing maturity models lack DT implementation comprehensively and quantitatively (Chen et al., 2021). The levels and advancement of digitalisation in the AEC industry have different capabilities. The AEC industry is fragmented into the pillars of

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Industry 4.0: the Internet of Things (IoT), big data, augmented reality, advanced visualisation, Virtual Reality (VR) and simulation, additive manufacturing, system integration, cloud computing, autonomous systems, and cybersecurity (Pour Rahimian, Dawood, Ghaffarianhoseini, & Ghaffarianhoseini, 2022). There are issues with minimising the cost and manual labour of the automated segmentation of individual instances for more efficiency and valuable outcomes for geometric digital twins (Agapaki & Brilakis, 2021).

The global goals to address environmental challenges in the construction industry and operational assets' life cycles warrant a change of approach. The concept of digital twins' application as one of the solutions has a knowledge gap for its adoption in the industry. Integrating IoT, BIM and AI as parts of the digital twin to automate the monitoring and control of emissions from existing assets evidence interactive trends and patterns from collected data through the integration of machine learning. It enhances facility management as a potential for net-zero targets. However, there are limitations, such as digital shadow usage instead of real-time digital twins (Arsiwala, Elghaish, & Zoher, 2023). Nearly Zero Emission Buildings (NZEBs), reducing the energy consumption of the existing building is necessary, and the need to manage energy consumption is supported (Agostinelli, Cumo, Guidi, & Tomazzoli, 2021; Francisco, Mohammadi, & Taylor, 2020; Kaewunruen, Rungskunroch, & Welsh, 2019; Tang et al., 2023). Still, the viability of digital twins' financial and technical implementation has been questioned. However, the BIM-Digital Twin integration for detailed energy stimulation was used in a case study in the United Kingdom (UK); it was proven that digital twin implementation has the potential for a 23-year return period for renewable technology for an existing building (Kaewunruen, Rungskunroch, et al., 2019).

The DT-based approach could provide an adaptive comfort model, energy-saving strategies, and building comfort optimisation. Exploiting the digital twin approach supports sustainability decisions through the whole adoption cycle for climate issues and environmental challenges; it can be used for energy-saving in different types of buildings (Tagliabue et al., 2021). The effectiveness of implementing a digital twin for asset management is lacking for adoption in the housing sector and industry practitioners for predictive monitoring in buildings (Arsiwala et al., 2023). Existing research indicates that DT is still needed in stimulation during system run-time and different lifecycle phases in academic and industrial communities (M. Liu, Fang, Dong, & Xu, 2021).

With all the above in mind, this paper aims to develop a direction for research on digital twin applications in existing buildings towards achieving the net-zero target. The objectives are 1) to explore the challenges in using DT in existing buildings? And 2) to investigate how the built environment sector could use predictive maintenance system-based DT in the UK. The rest of the paper sections are 2) the adopted methodology in the study, 3) digital twins research for predictive maintenance, 4) research significance and contributions, and 5) the conclusion and recommendations for future studies to leverage the adoption of DT for predictive maintenance in the built environment.

## 2. METHODOLOGY

According to Webster and Watson (2002), the literature review aims to uncover the past to identify the gaps and chart future directions by identifying aspects that research should focus on. The benefits of using a systematic literature review in this paper are: 1). to identify where evidence may be lacking, contradictory or inclusive, and 2). justify why a problem is worthy of further study (Aromataris & Pearson, 2014). See Figure 1.

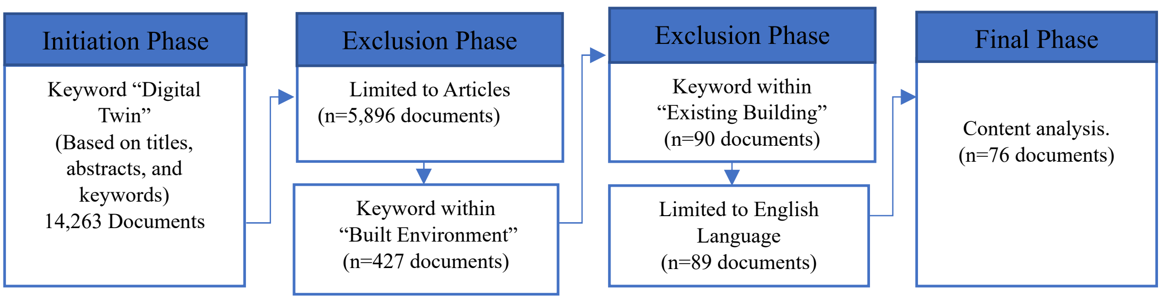


Fig 1: Systematic Selection Flowchart

The systematic review methods framework is based on the Initiation, Exclusion, Exclusion and Final phases criteria based on research studies by Kitchenham et al. (2010) and Mastan, Sensuse, Suryono, and Kautsarina (2022). For the inclusion and exclusion stage, Scopus was used to filter relevant keywords for the study to reduce the likelihood of bias, as the largest database of peer-reviewed research compared with Google Scholar or Web of Science and PubMed. The keywords searched from titles and abstracts were "Digital Twin", "Built Environment", and "Existing Building" as the relevant terms to the research study and the domain, which were used on papers published over a timeframe between 2018 and the present.

Articles were chosen from different journals written in English. The selected articles were then narrowed to 76 articles in the Scopus database using the process described in Figure 1. The articles were categorised broadly into 1). BIM-DT Maturity Model 2). DT in the AEC industry 3). DT for Maintenance of Buildings 4). DT for Net Zero in Existing Buildings (NZEB) 5). DTs for Facility Management 6). DTs for Energy Management. However, the emphasis was an overview analysis of the DT technology for existing buildings management within the AEC industry. NVivo software was used for the systematic content review and visualisation analysis. The NVIVO software aided rigorous data extraction, evaluation, and categorisation of the large amount of data generated by the 76 selected articles.

## 3. DIGITAL TWINS RESEARCH FOR PREDICTIVE MAINTENANCE

The following sub-sections will show cases of the attributes and challenges of DT adoptions within the articles selected. These are: 1). BIM-DT Maturity Model 2). DT in the AEC industry 3). DT for Maintenance of Buildings 4). DT for Net Zero in Existing Buildings (NZEB) 5). DTs for Facility Management 6). DTs for Energy Management for an overview of limitations faced within the built environment.

### 3.1 BIM-DT Maturity Model

The emergency of real-time connectivity and deployment in an environment increases the potential for DT concepts in the built environment. Noted to be in an early stage of adoption, the analysis indicated unrealised and unexploited possibilities of the DT concept for building management; further studies as a baseline were recommended (Deng, Menassa, & Kamat, 2021). BIM and DTs are disruptive technologies to be embraced by the construction industry due to the recent increase in advanced automation and autonomous technologies at the organisation, and need to be adequately leveraged (Sepasgozar et al., 2023). Notably, DT proved to be a valuable tool for the entire lifecycle management of buildings since BIM cannot handle the sensory information and complexities of existing buildings (Banfi, Brumana, Salvalai, & Previtali, 2022).

Existing BIM standards (ISO 19650) were proposed to promote a better interoperable digitalised built environment to develop DTs in the AEC sector (Nour El-Din, Pereira, Poças Martins, & Ramos, 2022). DT-BIM-based model reduced load bearing and risk in existing highway infrastructures. However, concerns were information collection and analyses for inspection, maintenance planning, and data sharing and visualisation limitations. The BIM-based model provided solutions and insights for high-quality construction and maintenance to minimise rapid degradation and component failures in infrastructures. Owners and stakeholders would achieve higher operational efficiency and sustainability outcomes over the life cycle, especially the expensive phases (Kaewunruen & Lian, 2019). DT-BIM-based model is recommended for the whole life-cycle mitigation of risks and uncertainties of exposure to extreme weather conditions for construction industry stakeholders (Kaewunruen, Sresakoolchai, Ma, & Phil-Ebosie, 2021).

Integrations of human-centred approaches, Virtual Design Construction (VDC), digital twin and artificial intelligence will transform the future of the AEC industry and create research opportunities. The integrations can simultaneously optimise, predict, and provide significant cost savings for the industry work processes, which should be noted for the main line of future research (Rafsanjani & Nabizadeh, 2023). BIM, IoT, and AI-supported systems are beneficial for prediction and data-driven retrofitting strategies, a step towards achieving the net-zero targets (Arsiwala et al., 2023). Multi-layer DT called BIM-IoT-Data integration (BIM-IoTDI) indicated capabilities to overcome interoperability and be suitable for smart buildings (Eneyew, Capretz, & Bitsuamlak, 2022). AI, DTs, and scanning technologies are valuable for maintenance strategies. However, some challenges are associated with technological, cultural, market and regulatory factors (Çetin, Gruis, & Straub, 2022).

Two-directional interactions between humans and computers should be part of the development to reach a high maturity level. Further studies, including advanced technologies like AI, BIM, and Geographic Information System (GIS) cloud computing, are essential to cope with the complex urban challenges of multidisciplinary DTs (Masoumi, Shirowzhan, Eskandarpour, & Pettit, 2023). Automation and robotisation are resources for management improvement in construction and existing buildings-the BIM data are programmed to a robot and visual format as the digital twin of the real-world building revealed valuable results that need further studies on the data reliability, interoperability of the BIM and 3D-Robot connections, and update of the BIM model based on robot feedback (Pauwels, de Koning, Hendrikx, & Torta, 2023). Likewise, the Mobile BIM Technology (MBT) functions can help researchers and practices in digitalisation, lean construction, evaluation perspectives and data-driven approaches to enable DT. Legal and security perspectives should be considered (Jowett, Edwards, & Kassem, 2023).

The proposed DT and Cloud BIM-Extended Reality (XR) platform development using the Scan-to-BIM-to-DT process to a 4D multi-user live app to improve building comfort, efficiency and costs was validated for energy improvements for existing buildings and façade renovations (Banfi, Brumana, Salvalai, et al., 2022). Implemented DT used scan-to-BIM with sensor data as an Industry Foundation Classes (IFC) BIM platform to monitor the structural health of the building walls. It can benefit FMs for planning and maintenance activities and the long life cycle of a building (Longman, Xu, Sun, Turkan, & Riggio, 2023). The lack of a clear process roadmap is partially a factor. Still, Digital Twin Construction was proposed as a comprehensive construction mode that prioritises closing the control loops instead of an extension of BIM tools integrated with sensing and monitoring technologies (Sacks, Brilakis, Pikas, Xie, & Girolami, 2020). DT cannot be limited to the focused aspects like 3D modelling, monitoring, and visualisation of DTs (Masoumi et al., 2023). Tagliabue et al. (2021) supported shifting from a static sustainability assessment to a digital twin-based and IoT-enabled dynamic approach for real-time evaluation, sustainability criteria control, and user-centred viewpoint in the built environment. A roadmap is required to support decisions and policymakers to aid implementations for the next ten years (2030) (Sepasgozar et al., 2023).

It should be noted that DTs are extensions of engineering information (EI) leveraging modern information and communications technology (ICTs) and do not have their unique technical characteristics (Zhou et al., 2022). The integration of DT roles as an observer, analyst, action executor and decision-maker is useful in helping practitioners systematically plan DT deployments, clearly communicate goals and deliverables, and lay out a strategic vision (Agrawal et al., 2023). Digital Twins are the future of the metadata required for a socio-technical collaborative and sustainable ecosystem based on a virtual representation of the physical instance in a real-time operational state superseding static 3D- Building Information Modelling or traditional 2D of assets for the multidisciplinary AEC domains for operational efficiency and cost reduction (Pregnolato et al., 2022) updated information to analyse and optimise ongoing design, planning and production, lean construction, and data-centric construction management (Sacks et al., 2020).

The widespread traction of DTs for constructed facilities projects reveals the benefits of DTs as the ability to reduce operating costs and human error, automate energy demand, manage assets throughout their lifecycle, and structural health monitoring in real-time (Khallaf et al., 2022) with robot-Assisted reality capture in larger spaces (Xu, Xia, You, & Du, 2022). The application of DTs and Machine Learning helps predict and analyse prestressed steel structures needed for intelligent monitoring techniques and control methods to ensure safety (Z. Liu, Yuan, Sun, & Cao, 2022). IoT and DT connection and integration produce real environments to boost automation, Industry 4.0 transformation and cost-effectiveness (Al-Dhlan, 2021) with robot-assisted reality capture in larger spaces (Xu et al., 2022). Likewise, DTs in the UK are used for highway asset management to achieve minimum human input and have very high accuracy (Jiang, Ma, Broyd, Chen, & Luo, 2022).

Multi-layer DTs proved to be a valuable tool for the entire lifecycle management of buildings since BIM cannot handle the comprehensive DT technology that can be supported with socio-technical approaches to reach maturity. The integration of IoT with DT has proven to be valuable with the application of DTs in the multidisciplinary AEC domains, even though some challenges were indicated in Tables 1-5.

## 3.2 DT in the AEC Industry

The articles in Table 1 are on DT research in the AEC Industry and the challenges encountered. Infrastructure assessment and construction management were highlighted.

Table 1. Articles on DTs studies within the AEC Industry.

| Author/Year | Focus of Study | Employed Tools | Challenges /Limitations |
|---|---|---|---|
| (Camposano, Smolander, & Ruippo, 2021) | Awareness of DT of Built assets relative to the software ecosystem | Interpretive analysis of semi-structured interviews | Inter-organizational relationships, data sharing, and technical expertise |
| (Çetin et al., 2022). | Adoptions of digital technologies in social housing | Multiple- case study Circular Economy Digital Twins framework | Technical, cultural, market and regulatory issues. Misalignment of supply and demand. Data quality and sharing |
| (Eneyew et al., 2022) | Interoperability of smart-building DTs | BIM-IoT Digital integration | Autonomous query decision and data sharing |

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|---|---|---|---|
| (Jowett et al., 2023) | Mobile BIM technologies taxonomy in field BIM interactions with construction management functions | A longitudinal case study over 12 months, two project workshops, expert interviews and an industry survey at project, enterprise, and industry levels. | Lack of delineation between related terms used. |
| (Kaewunruen et al., 2021) | Vulnerability assessment and risk-based maintenance of infrastructures | BIM-DT based model | Automated interaction of data, 3D modelling human resources and standards, IT software natural and human risk assessments. |
| (Longman et al., 2023) | The implementation of DTs to support structural health monitoring (SHM). | Scan-to-BIM approach in IFC-BIM platforms. | Data integrations and project infrastructure |
| (Nour El-Din et al., 2022) | Status of DTs and the evolution of the concept of DTs for construction Assets | Systematic Review | Lack of data standardisation |
| (Pauwels et al., 2023). | Live semantic data transfers from building digital twins for robotic navigation | BIM-based model | Automation, data reliability and standards |
| (Rafsanjani & Nabizadeh, 2023) | Cost-saving DT capabilities in construction and operational phases | VDC-DT based model + VR+AR | Technical expertise, Compatible software, Automation, Human-centric scenarios, real-time data senses and analysis. |
| (Sacks et al., 2020) | Digital twin information systems to achieve closed-loop control systems to monitor construction. | Conceptual analysis | Lack of comprehensive information system and knowledge |

## 3.3 DT for Maintenance of Buildings

Table 2 comprises articles on building maintenance and the challenges of adopting DTs. Emphases are mostly on historical building restoration.

Table 2. Articles on DTs exploration for maintaining structural buildings.

| Author/Year | Focus of Study | Employed Tools | Challenges /Limitations |
|---|---|---|---|
| (Ali, Alhajlah, & Kassem, 2022) | The status and future trends in building information modelling (BIM) | Systematic literature review (SLR) methods through co-occurrence and co-citation analysis. | The complexity of the project, integration of components and data |
| (Banfi, Brumana, Landi, et al., 2022; Khalil et al., 2021) | Data categorising in the digital documentation of heritage buildings | HBIM model | Protection and longevity of heritage buildings data. Interoperability and BIM standardisation or extended reality environments and data formats. |
| (Cardinali et al., 2023; Moyano, Carreño, Nieto-Julián, Gil-Arizón, & Bruno, 2022; Noronha Pinto de Oliveira e Sousa & Correa, 2023). | Digital twins for heritage buildings. | Historic building information modelling (HBIM) geometric model. | Data acquisition constraints and difficulties, the scale of the building. |
| (Daniotti et al., 2022). | BIM-DT Based Interoperability for efficient renovation in buildings | BIM-DT based model | Data integration and standardisation processes |
| (Pan, Braun, Brilakis, & Borrmann, 2022) | How to enrich geometric digital twins of buildings, particularly emphasis on capturing small vital entities in buildings | 3D point cloud + AI-based image segmentation | Variation in objects, data collection and occlusion of the environment |
| (Porsani, de Lersundi, Gutiérrez, & Bandera, 2021) | Evaluates of an automated or semi-automated BIM to BEM workflow in buildings | BIM-BEM model | Technical expertise, large and complex buildings |
| (Sagarna et al., 2022) | Documentation and displaying inspection-related information in BIM models to generate a dynamic information model in buildings. | Innovative BIM model-State of Conservation Assessment BIM Model (SCABIM) | Dynamic open-source data integration, technical workforce, and equipment |
| (Tan, Leng, Zeng, Feng, & Yu, 2022). | DT-3D digital replicas record and heritage buildings survey | BIM multi-methodological approach, | Obstruction of the surrounding environment and data exchange. |

## 3.4 DT for Net Zero in Existing Buildings (NZEB)

Table 3 includes related articles on efforts towards NZEB and the challenges faced while adopting DTs. BIM-based models were majorly used to integrate data for simulations.

Table 3. Articles on NZEB research using DTs.

| Author/Year | Focus of Study | Employed Tools | Challenges /Limitations |
|---|---|---|---|
| (Godager, Onstein, & Huang, 2021) | BIM in asset and facilities management. | Enterprise BIM (EBIM) | Data integration, security and management, Naming convention, Data infrastructures, and suitable common data environment. |
| (Kaewunruen & Xu, 2018) | Assessing the carbon footprints of a building in the design process using BIM technology. | BIM-enabled data visualisation + API | Computational and technical expertise, natural light area and data extraction |
| (Kaewunruen, Peng, & Phil-Ebosie, 2020; Kaewunruen, Sresakoolchai, & Kerinnonta, 2019) | Sustainability and vulnerability in buildings | DT + BIM | Computational and technical expertise, structural tolerances, and autonomous integration. |
| (Lu, Xie, Parlikad, Schooling, & Konstantinou, 2020) | BIM to digital twins for operation and maintenance | Smart asset management (DTs + AI + ML+ data analytics) | Technology, Organisation, information, and data standard-related issues. Domain alignment, Interaction between domain and all stakeholders |
| (Ochs, Franzoi, Dermentzis, Monteleone, & Magni, 2023) | Monitoring and simulation-based optimisation of two multi-apartment for NZEBs | MATLAB Simulink simulation +Building management system | Cost analysis, different heat sources, and simulation |
| (Shen, Ding, & Wang, 2022) | Whole-life-cycle net-zero-carbon buildings | DT +BIM | Building lifecycle stages. Automated system and dynamic sensor data |

## 3.5 DT for Facility Management

Related articles on building facility management and the challenges of adopting DT approaches are in Table 4. Studies were mainly based on existing buildings' operation and maintenance phases.

Table 4. Articles on facility management research using DT.

| Author/Year | Focus of Study | Employed Tools | Challenges /Limitations |
|---|---|---|---|
| (Badenko et al., 2021) | Integration of digital twin and BIM technologies in FM | DT +BIM ("Factories of the Future" framework) | Systems integration, Training and investment cost and technical expertise |
| (Chacón et al., 2023) | Structural Health Monitoring (SHM) systems within the DT platform | BIM -DT-based model | Data integration and interoperability, and multiple sources pipelines. |
| (Chen et al., 2021) | An innovative maturity model for measuring digital twin maturity for asset management. | DT +BIM (Gemini Principles) | Domain environment, technical expertise, Cultural and policy influence |
| (Costa, Arroyo, Rueda, & Briones, 2023) | A ventilation early warning system (VEWS) for FM | Smart Campus Digital Twin (SCDT) framework (BIM +IoT +AI) | Characteristics of building workspaces, data integration and interoperability of systems |
| (Fialho et al., 2022) | Prototyping a BIM and IoT-based smart lighting maintenance system for the FM sector | BIM and IoT-based | Lack of consistent tools, methods, and devices for measuring building components' performance and restrictions in research resources |
| (Harode et al., 2023) | System architecture for a digital twin in a healthcare facility (FM) | Structured literature search and analysis +DT | Data integration, standard, environment, interoperability, and technical expertise |
| (H. H. Hosamo, Nielsen, Kraniotis, Svennevig, & Svidt, 2023a, 2023b) | Automated fault source detection and prediction for comfort performance evaluation of existing buildings | DT + BIM model based on Bayesian networks (BNs). | IoT connectivity, BIM systems, technical and computational expertise, interoperability of systems, occupant profile and owner funding. |
| (Jiao et al., 2023) | A sustainable digital twin (DT) model of operation and maintenance for building infrastructures, | DT +Bayesian network (BN) + Random Forest (RF) | Small buildings, equipment, building space, data collection and systems |

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|---|---|---|---|
| (Khajavi, Tetik, Liu, Korhonen, & Holmstrom, 2023) | DT for safety and Security in building Lifecycle | DT +BIM | Awareness, cost, data type, real-time studies, and access to case studies on other buildings |
| (Levine & Spencer, 2022) | Post-Earthquake Building Evaluation. | BIM-Based Digital Twin Framework | Building components and alignment, BIM systems and computational systems |
| (Lu, Xie, Parlikad, & Schooling, 2020; Xie, Lu, Rodenas-Herraiz, Parlikad, & Schooling, 2020) | Visualised inspection system for monitoring during daily Operation and Maintenance | AR-supported automated environmental anomaly detection and fault tree analysis method | Environmental conditions, Data collection, processes, and computational expertise |
| (Moretti, Ellul, Re Cecconi, Papapesios, & Dejaco, 2021) | Integration of GIS and BIM for built environment condition assessment in asset management decision-making | DT +BIM +GIS (Geographic Information System) | Technical complexity, digital expertise, automatic semantic mapping, stakeholders, information gathering, data and systems integrations |
| (Pan, Braun, Borrmann, & Brilakis, 2022) | How to generate geometric digital twins of the indoor environment of buildings automatically. | 3D deep-learning-enhanced void-growing approach | Computational efforts, point cloud data and occlusion of the environment |
| (Rampini & Re Cecconi, 2022) | Artificial intelligence in construction asset management for sustainability | Literature review +bibliometric analysis | Time-consuming and labour-intensive, technical expertise, Data collection and processes |
| (Shahinmoghadam, Natephra, & Motamedi, 2021) | The benefits of BIM, the IoT and Virtual Reality (VR) for thermal comfort conditions | BIM+ IoT +VR | Sensor placement, Building space, and semi-automated registration of the thermal image's method |

## 3.6 DT for Energy Management

Articles focusing on the efficiency of building energy management and the challenges of adopting DT approaches are in Table 5, exploring energy cost and consumption reduction.

Table 5. Articles on energy management research using DT.

| Author/Year | Focus of Study | Employed Tools | Challenges /Limitations |
|---|---|---|---|
| (Borja-Conde, Witheephanich, Coronel, & Limon, 2023). | Automatic thermal models of existing buildings for energy management | High-fidelity simulator software TRNSYS | ML techniques, the accuracy and robustness of building thermal behaviour modelling |
| (Corrado, DeLong, Holt, Hua, & Tolk, 2022). | Green metrics and digital twins for Sustainability planning and governance | Published literature review | Real-world metrics standard, computational decision support |
| (Delgado et al., 2023) | The interconnection between BIM and building energy modelling (BEM) for energy cost reduction. | BIM-BEM (Drone based) framework | Technical expertise and occlusion of the environment |
| (H. Hosamo et al., 2023). | A digital twin of heating, ventilation, and air conditioning for optimisation of energy consumption and thermal comfort based. | BIM +DT (MATLAB + Artificial neural network + multi-objective genetic algorithm) | Data standards and type, Ontology techniques to integrate BIM, energy management, and thermal comfort data in one framework. |
| (Hosseinihaghighi et al., 2022) | Assessment of housing stock and smart thermostat data in support of energy end-use mapping and housing retrofit program planning | Smart thermostat integration model | Data quality and collection, Classification standard terminology, occupants' behaviours, Building characteristics, real-time data integration and interoperability |
| (Kaewunruen, Sresakoolchai, et al., 2019) | Reconstruction design of an existing building energy building goal | BIM-based digital twin | Data integration, financial analysis, different functions of renewable technologies, and computational supports. |
| (Lamagna, Groppi, Nezhad, & Piras, 2021). | Digital twins for smart energy management system | A comprehensive literature review | Big data, communication protocols, lack of regulation and a transparent market, uncertain and unclear framework, different versions of DTs and algorithms. |
| (Spudys et al., 2023). | Operational energy performance of buildings with the use of digital twins | DT model | Lack of required equipment, digital environment, infrastructure, occupant behaviour and building automation systems |

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|---|---|---|---|
| (Tang et al., 2023). | Vertical greenery system (VGS) renovation for building energy efficiency analysis based on digital twin | DT + BIM model | Direction and location of the building and environmental conditions |
| (Zhao et al., 2022). | Evaluation of public toilet ventilation design schemes through a digital twin to maintain high environmental quality | BIM-based digital twin | Building cost and construction simulations computations, cloud-based services, computations support |

## 4. RESEARCH SIGNIFICANCE AND CONTRIBUTION

The research's significances are to remove silos and allow data and information sharing for effective and holistic implementation and interactions that reduce wastage and costs in retrofitting and energy consumption in existing buildings as one of the largest energy consumptions. The research would add insights into energy retrofit and management cost as part of Net-zero strategies in the UK.

Analysing the existing literature on DT attributes and challenges provides a glimpse into the reality of insufficient research studies on DT globally, especially in the UK; 25 articles from the UK were within the research scope. The analysis would contribute to the body of knowledge in the UK and globally. The literature pointed out the confusion of DT as an extended branch of BIM. However, DT has been revealed as a multi-objective and multi-scale technology field within the I4.0 that requires an advanced analytical approach through data and stimulation to support comprehensive and predictive decision-making to save costs and wastages. The door is widened for researchers to explore viable solutions to overcome the challenges uncovered in the literature to leverage DT benefits within the built environment.

The research would contribute and benefit suppliers (technologies and platforms), homeowners, landlords, policymakers, operation and maintenance (O&M) managers, facilities management (FM), and the research community to reduce costs with predictive decisions based on proactive maintenance rather than reactive maintenance. It will replace speculative retrofitting actions with factual insights for different types of existing structural buildings, occupancy behaviour and locality. There are reasonable limitations within the period of the systematic review and the platform used to select optimal articles based on the research topic due to the low number of publications. However, more publications could have been added from other platforms like Google Scholar but not peer-reviewed to ascertain the quality required to maximise the value of the review.

## 5. CONCLUSIONS AND FURTHER RESEARCH

Digital Twins can integrate information from multiple sources to replicate the operation of the physical spatial asset in real-time for stimulations and predictive insights**.** The application of digital twins is still in an emergency phase as a valuable digital technologies advancement, especially with the built environment and the AEC industry in the UK. There needed to be more publications on the research topic. The paper set out two objectives: 1) to explore the challenges in using DT in existing buildings. And 2) to investigate how the built environment sector could use predictive maintenance system-based DT in the UK.

DT needs to be more understood and consistent in the application or technical tools usage from literature. In addition, practitioners, AEC managers and academics need more proper knowledge and technical expertise on digital twins as part of the I4.0, as evidence from the literature resulted in low empirical case studies. The complexity of real-time data integration and interoperability were highlighted as part of the challenges. Digital Technologies can be pardoned as a common word for I4.0, are the enabler of all societies and organisations' productivities, previously a buzz, now overtaken by Artificial Intelligence (AI). The direction to advance digital twins' adoptions in existing buildings towards achieving net-zero goals is realism 1). Training for applicable practitioners in the built environment for the AEC industry. 2). Affordable computations and simulation tools and systems 3). Cloud-based architecture infrastructure and services 4). Data integration and interoperability 5). Open sources collaboration 6). Socio-technical influences and sustainable policies.

Finally, based on the literature, predictive maintenance system-based DT with intelligent analysis supported comprehensive and consistent solutions for rehabilitation, operation, and maintenance management of existing building life cycle management. However, more steps are needed to leverage the benefits: the future case study for the built environment sector to use predictive maintenance system-based DT in the UK are 1). the depth of knowledge of DT with professionals in the built environments, 2). A standard benchmark framework for DT adoptions 3). Available and accessible computations simulation tools, and systems 4). Funding for the research 5). Socio-Technical influences and training.

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