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Energy Informatics (2024) 7:11
https://doi.org/10.1186/s42162-024-00313-7

Energy Informatics

REVIEW

Open Access

A review of building digital twins to improve energy efficiency in the building operational stage

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Abstract

The majority of Europe's building stock consists of facilities built before 2001, presenting a substantial opportunity for energy efficiency improvements during their operation and maintenance phase. Digitalizing these buildings with digital twin technology can significantly enhance their energy efficiency. Reviewing the applications and trends of digital twins in this context is beneficial to understand the current state of the art and the specific challenges encountered when applying this technology to older buildings. This study focuses on the application of digital twins in building operations and maintenance (O & M), emphasizing energy efficiency throughout the building lifetime. A systematic process to select 21 pertinent use-case studies was performed, complemented by an analysis of six enterprise-level digital twin solutions. This was followed by an overview of general characteristics, thematic classification, detailed individual study analyses, and a comparison of digital twin solutions with commercial tools. Five main applications of digital twins were identified and examined: component monitoring, anomaly detection, operational optimization, predictive maintenance and simulation of alternative scenarios. The paper highlights challenges like the reliance on Building Information Modeling (BIM) and the need for robust data acquisition systems. These limitations hinder the implementation of digital twins, in particular in existing buildings with no digital information available. It concludes with future research directions emphasizing the development of methods not solely reliant on BIM data, integration challenges, and potential enhancements through AI and machine learning applications.

Keywords: Digital twin, Energy efficiency, Operation, Maintenance, Building Information Modeling (BIM), Energy Modeling, IoT system

Introduction

Buildings within the European Union consume nearly 40% of the total energy consumption (European commission 2018). According to the International Energy Agency (IEA), the buildings and construction sector is responsible for approximately 36% of total emissions (European Parliament 2023), with 22% coming from residential buildings, 8% from non-residential buildings, and 6% from construction projects and industries (IEA 2019). Because of this, the buildings sector holds great potential for achieving cost-effective improvements in efficiency and substantial proportional reductions in greenhouse gas emissions (European commission 2020).

To meet the ambitious energy and environmental targets set for 2030 and 2050, the EU has placed a strong emphasis on the construction and buildings sector through the energy performance of buildings directive (European Parliament 2010). The revised directive aims to increase the rate of building renovation, specially for the worst-performing buildings and supports better air quality, the digitalisation of energy systems for buildings and the roll-out of infrastructure for sustainable mobility.

However, the global implementation of energy efficiency measures in existing buildings is lacking and falls far short of the necessary actions to achieve net-zero carbon dioxide emissions by 2050. This is evident from the fact that existing buildings still make up the majority, accounting for over 97% of the building stock (Arup 2023b). The EU's building stock, for instance, consists of more than 220 million units, with 85% of them constructed before 2001. It is projected that around 85–95% of these buildings will still be in existence by 2050 (Fufa et al. 2021). The majority of these buildings are energy inefficient, relying on fossil fuels for heating and cooling and employing outdated technologies and wasteful appliances.

In general, the majority of buildings are in the operational stage of their life cycle. This also means that, depending on the age of the building, the available information and level of digitalisation can vary greatly. A considerable opportunity arises for incorporating digital technologies to contribute to reduce energy demand as well as enhance comfort. This transformation aligns with the continuous progress in communication and information technologies, together with the advancement and establishment of interconnected and intelligent grids. These buildings should adapt their operations to changes in the energy grid and occupant behaviour, as well as enable strategic maintenance. By reducing energy consumption in buildings, it is possible to reduce greenhouse gas emissions and mitigate the impact of climate change. Additionally, improving energy and maintenance efficiency in buildings can also result in cost savings for building owners and occupants, as well as potential better indoor comfort levels (Volk et al. 2013). The digitization of building data is a key catalyst in this context, expanding rapidly across various sectors within the building industry and construction sector.

The increasing interest to de-carbonize the building stock, the public directives aimed towards improving energy efficiency and the increasing capabilities of digital and statistical methods are major incentives to describe the current state of the digital twins for buildings technologies. This research aims to systematically evaluate strategies for boosting energy efficiency in buildings with diverse digital integrations. Emphasizing the role of digital twins in operational energy optimization, the research will examine their usage in building operations, identifying prevalent implementation patterns. Furthermore, it will scrutinize case studies to evaluate the advantages and outline the current and potential capabilities offered by digital twin technologies in buildings.

Recent developments on digitalisation for the construction sector have been connected with Building Information Modeling (BIM) (ISO 2021) models providing a source of truth during the design and construction phases of a building. It facilitates the collaboration between Architecture, Engineering and construction (AEC) professionals, making it widespread over the last decades (Lu et al. 2020a). Furthermore, BIM models have also been used for running simulations to provide insights about the expected performance of the building or to assist the construction process (Penttilä et al. 2022).

However, traditional BIM techniques provide only static analysis with no data-exchange between sensors and the digital model. This is a problem addressed by the concept of digital twins.

Digital twining techniques, initially utilized within Aerospace and Manufacturing, have now extended to applications throughout a building's life cycle as shown in Fig. 1. A digital twin is a digital and/or mathematical model of a physical asset which integrates sensor readings and a form of data exchange between the digital model and the physical asset. The trend of utilizing digital twins and modeling for buildings has been gaining popularity (Bortolini et al. 2022). With the help of an Internet of Things (IoT) system comprised of sensors, a data pipeline and a data processing and analysis system, the BIM models can be extended into Digital Twins which reflect in a more precise way the behavior and properties of the modeled building, during any phase of its life-cycle (Lu et al. 2020b; Bortolini et al. 2022; Hou et al. 2023) (Fig. 2).

The potential of connecting BIM and IoT-based data sources is a relatively new development. As a generalization, BIM and IoT data offer complementary views of the project that together supplement the limitations of each. BIM models offer high fidelity representations of the project at the component level. IoT data can bring to the table near-real-time operation data and performance statistics (Lu et al. 2020b).

An obstacle impeding the broad adoption of digital building twins is that a significant number of the constructions present in the usual city were designed and built before the digital era. At the same time, implementation and completeness of BIM models in recent buildings is also scarce (Volk et al. 2013). As a result, the

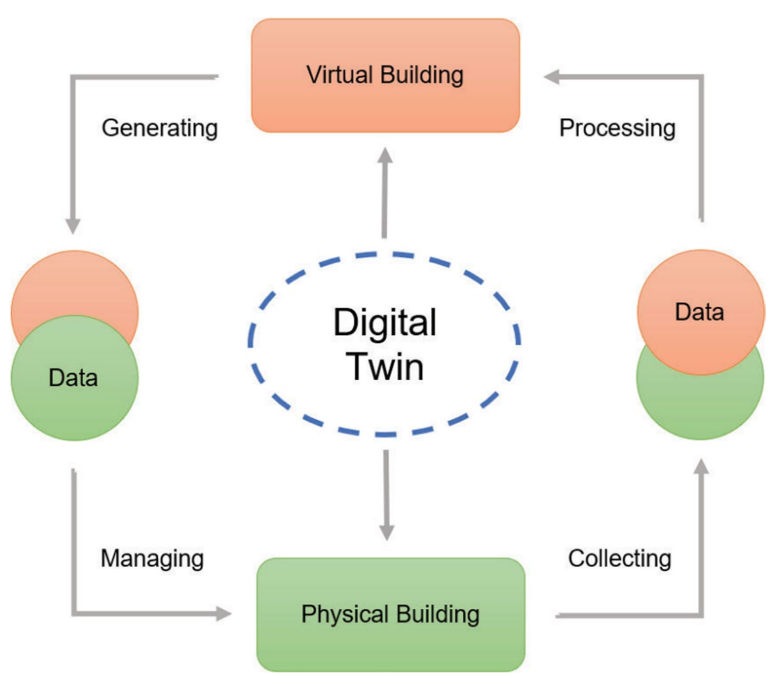

Fig. 1 Diagram of a building digital twin (Jradi and Bjørnskov 2023)

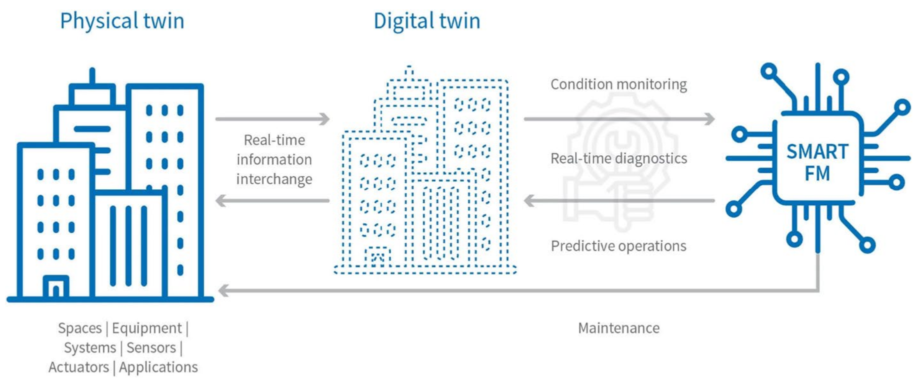

Fig. 2 Benefits of digital twins for O & M in buildings (Pressac 2018). A Digital twin for buildings can enable services that enhance the building operation stage

incorporation of IoT technologies and software might not be easily supported by an existing and accessible BIM model.

Given the potential benefits from implementing digital twins in the built environment, the trends to use BIM models for achieving digital twins and while also acknowledging the limitations of this method due to the older age of much of the building stock. The aim in this paper is also to provide a comprehensive overview of various digital twin use cases, both with and without the use of BIM. This includes an analysis of their architecture, implementation, and the benefits reported. Additionally, the study describes what a typical digital twin solution looks like for existing buildings and discusses both the benefits and challenges of implementing these technologies in the building stock.

The primary aim of this research is to systematically explore and evaluate a range of scholarly works focused on the application of digital twins in the domain of building operations and maintenance (O & M). To this end, a methodical review system will be employed.

Subsequent sections of this study detail the methodology adopted for selecting the case studies that form the basis of this analysis. The paper then proceeds to present an overview of the key findings from these studies, offering a thematic classification of the topics covered. This is followed by a comprehensive description of each selected case study. Later sections provide in-depth insights and discuss emerging trends observed in the research. This includes a critical analysis and comparison of digital twin solutions with existing commercial tools. The paper concludes by identifying the challenges faced in this field and outlining potential future directions for the technology.

Research methodology

"Search for previous studies" section and Fig. 3 provide an outline of the methodology used for this review. The process begins with a search of previous studies using platforms like Google Scholar and review papers. Cross-referencing and AI tools such as Elicit and ResearchRabbit are then used to compile scholarly articles. Studies pertinent to digital twins for building O & M that have a use case implementation are selected. Metadata from these studies is extracted for individual analyses and to classify them by topic. The analysis includes evaluating the level of data integration and the technology used. Studies that do not meet the criteria are discarded.

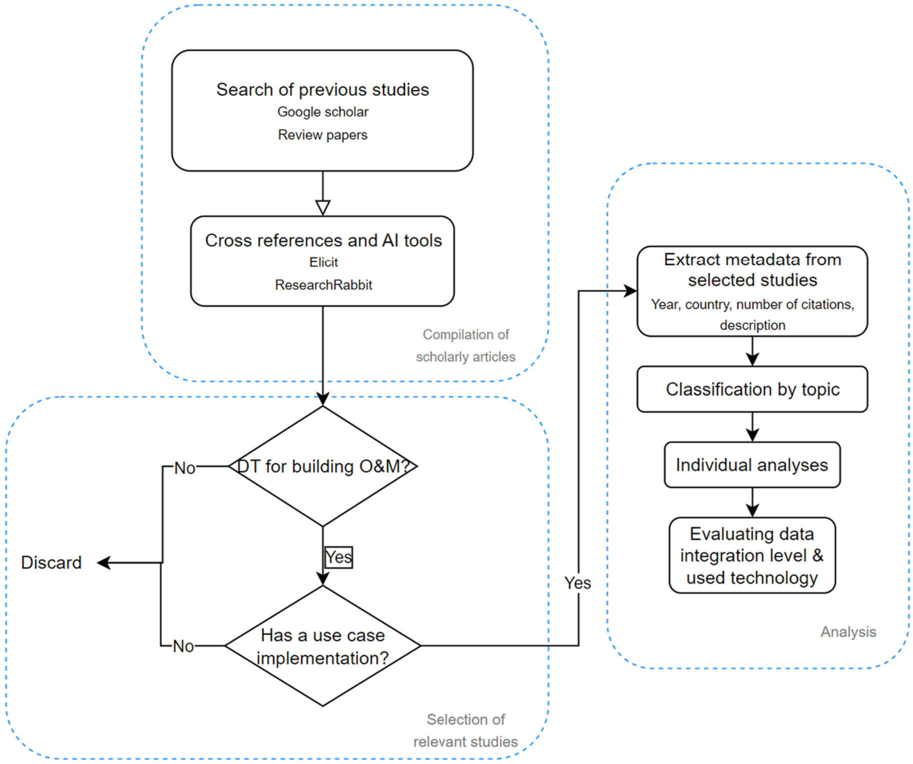

Fig. 3 Methodology for selecting and analyzing studies on digital twins for building operations and maintenance (O & M)

Search for previous studies

The initial screening for studies related to digital twins for building started by using a term search with Google Scholar, the search terms were:

- Digital twins for buildings.
- Digital twins for building energy efficiency.

The results where then prioritized based on the default google page rankings and the number of citations. The initial google scholar results revealed a large proportion of the papers related to the search terms to be reviewing papers. The initial selection of papers was made using the following heuristic:

1. Search of terms with google scholar.
2. Discard reviewing papers.
3. Choose papers with at least 5 citations provided by the default google scholar ranking.
4. Add papers with less citations but deemed relevant for the purpose of this study by using the AI cross-referencing tools.
5. Take into account two of the most recent review papers and 2 of the most cited review papers.

A filtering process followed using the scientific AI tool Elicit (2023) which uses language models and cross-referencing to provide summaries and an overview of the public feedback given to each paper. Additionally a cross-citation search was made with the help of the tool ResearchRabbit (2023) by generating a cross-citation graph as shown in Fig. 4 which provides an extended view of the relation between studies and unveils relevant studies in the field. This process yielded an initial group of 150 studies from the literature and 4 review papers was selected.

Adhering to the criteria of seeking *digital twins for buildings in their operational phase*, a list of studies using the Mendeley Reference Manager was compiled. This process yielded 21 use-case studies that were identified as pertinent to this review.

This study aims to provide a detailed overview of current digital twin solutions for modern buildings. To achieve this, a qualitative analysis of prominent market-available digital twin technologies was conducted. The focus was on solutions applicable during the operational phase of buildings, aligning with the digital twin definition presented in

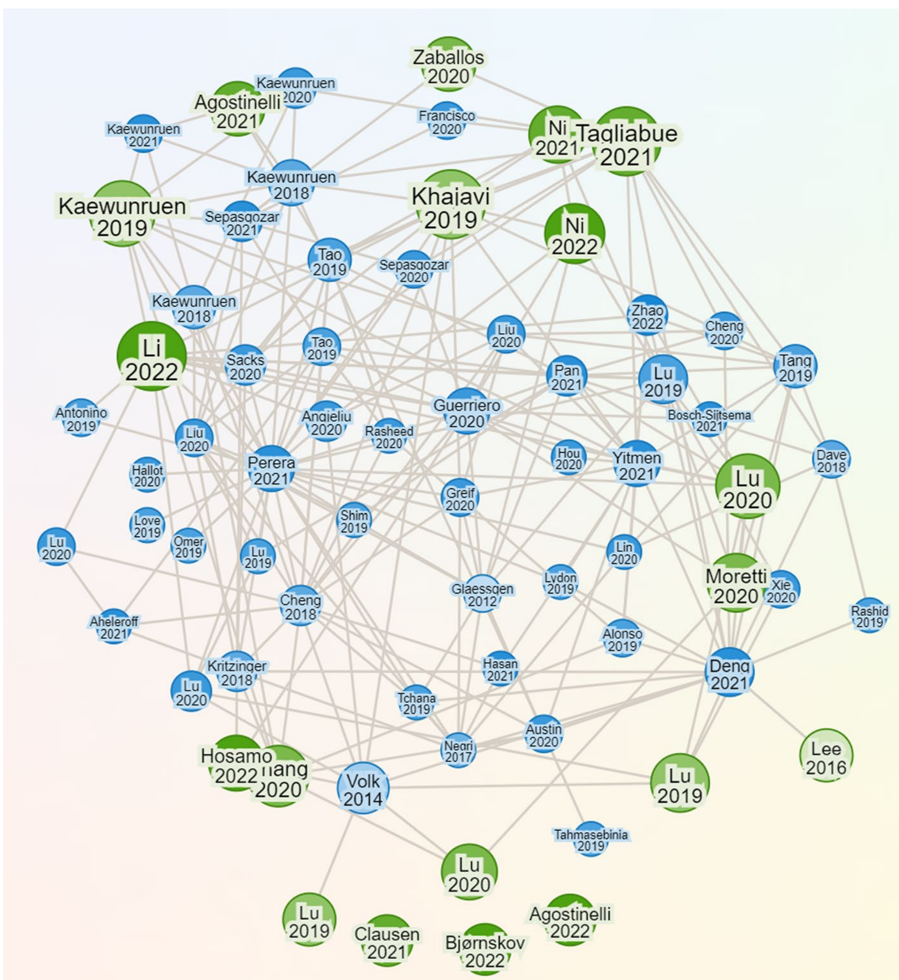

Fig. 4 Network graph from ResearchRabbit illustrating connections between research works. Use cases are marked in green, while related works are shown in blue. This interactive tool aids in discovering relevant papers that might otherwise be overlooked. However, its scope is confined to the range of public databases it utilizes

the previous "Introduction" section and Fig. 1. This analysis is conducted with the intention of shedding light on the fundamental distinctions between enterprise-level digital twin solutions and custom, in-house digital twin implementations. A process for collecting and scrutinizing six enterprise-level digital twin solutions, details of which are elaborated in the subsequent sections of this document.

Analysis process

In order to extract the most relevant characteristics from the list of articles, the following steps were taken:

Metadata extraction from the selected studies

From the resulting studies a data extraction was made, listing year, place of the study, number of citations and a brief description of the study. This description served as the starting point for the classification by topic.

Classification by topic

An attempt to provide a classification for the reviewed studies based on the main benefit of the use case implementation was made. All related to enhancements achieved during the operation stage.

Individual analyses

A more detailed analysis was carried out, reviewing the overall structure of the implemented digital twin solution, the reported results and the reported challenges.

Expected similarities & differences

Given the experimental nature of the use-cases in these studies, it is expected to find variations in the scope and magnitude of each digital twin implementation. Similarly, the specific advantages and applications of each will differ. The focus here is on identifying diverse modeling methods, as well as contrasting hardware and software architectures. There is a particular interest in studies that either incorporate Building Information Modeling (BIM) or proceed without it.

Despite these differences, some commonalities among the studies are also expected, particularly concerning the fundamental structure of the digital twins and the flow of information between the physical asset and its digital counterpart. Moreover, given the increasing prevalence of machine learning, its application is foreseen in many use cases. Lastly, it is anticipated that these digital twins will yield insights leading to enhanced efficiency, potentially even achieving this efficiency autonomously.

Results

General characteristics from metadata

These papers span from 2016 to 2023, showing a noticeable upward trend in the number of publications each year Fig. 5.

The use cases that draw the most attention are summarized in Table 1. However, the papers that gather the most attention are the review papers which compile a number of previous studies and analyze them (Boje et al. 2020; Yitmen et al. 2021).

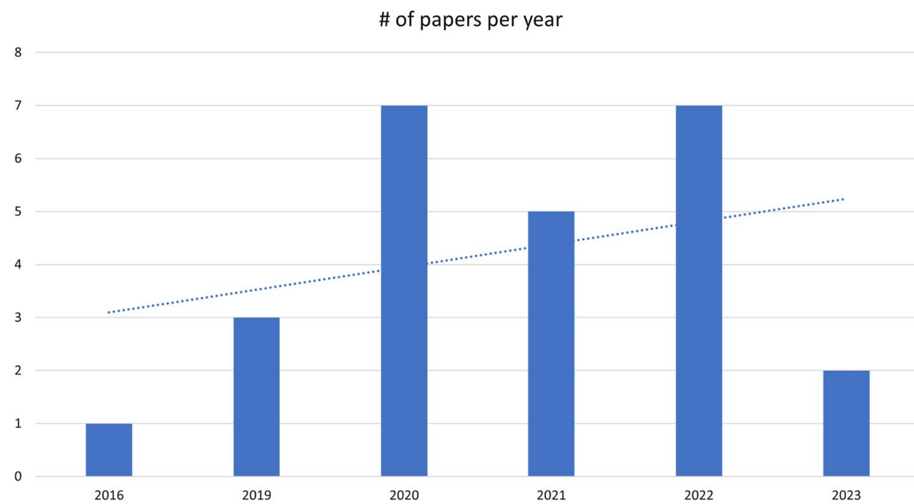

Fig. 5 Number of publications per year (As of September 2023)

Table 1 First five studies organized by number of citations

Name	Main author	Year	Country	Citations
Digital Twin: Vision, benefits, boundaries, and creation for buildings (Khajavi et al. 2019)	Khajavi, S. H.	2019	Finland	212
Developing a Digital Twin at Building and City Levels: Case Study of West Cambridge Campus (Lu et al. 2020c)	Lu, Q.	2020	UK	145
Digital twin aided sustainability-based lifecycle management for railway turnout systems (Kaewunruen and Lian 2019)	Kaewunruen, S.	2019	UK	122
Digital Twin Hospital Buildings: An Exemplary Case Study through Continuous Lifecycle Integration (Peng et al. 2020)	Peng, Y.	2020	China	62
Digital twin-enabled anomaly detection for built asset monitoring in operation and maintenance (Lu et al. 2020d)	Lu, Q.	2020	UK	56

Topics of the studies

Focusing mainly on the application and specific benefit obtained from the digital twin implementation, the identified recurrent topics were:

- Component monitoring
- Anomaly detection
- Operational optimization
- Predictive maintenance
- Simulation of Scenarios

Table 2 lists the category of each analyzed article.

Table 2 Themes identified and the respective papers addressing them

Theme	Publications
1. Component monitoring	Khajavi et al. (2019), Li et al. (2022)
2. Anomaly detection	Bjørnskov et al. (2022), Lu et al. (2020d, 2020)
3. Operational Optimization	Bjørnskov and Jradi (2023), Chiara Tagliabue et al. (2021), Clausen et al. (2021), Jradi and Bjørnskov (2023), Lee et al. (2016), Moretti et al. (2020), Peng et al. (2020), Wang et al. (2022), Zaballos et al. (2020), Zhao et al. (2022), Agostinelli et al. (2022)
4. Predictive maintenance	Hosamo et al. (2022), Ni et al. (2021, 2022)
5. Simulation of alternative scenarios	Agostinelli et al. (2021), Kaewunruen and Lian (2019)

Individual analyses

In order to provide a structured overview of the energy efficiency aspect of each digital twin use-case a general description of each case is provided, followed by a summarizing list highlighting the aspects that are more relevant to this review, these aspects are:

- Reported energy efficiency improvement: Qualitative overview of the claimed benefits of the study's implementation relative to energy efficiency only.
- Reported benefits: Qualitative overview of the claimed potential benefits of the DT, not only constrained to energy efficiency.
- Reported quantitative improvements from DT: Quantitative improvements reported from implementing the digital twin, for example, percentages of cost reduction and energy efficiency gains.
- Technology highlights: Key technologies utilized in the implementation/design of the DT, specially in the data acquisition and data processing aspect.

Component monitoring

Khajavi et al. (2019) described a research project involving four rounds of experimentation, resulting in the collection and analysis of over 25,000 sensor readings. These readings were used to create and test a limited digital twin of an office building facade element. The research introduces a method to establish a real-time digital twin using a sensor network. It entails gathering and analyzing specific environmental factors from the building's surroundings. While the study used a modest sensor network to monitor light, temperature, and humidity, the outlined framework could be adapted for a more comprehensive digital twin of the building's facade and interior. The paper also addresses technical challenges in digital twin creation and offers potential solutions. It proposes a sensor arrangement framework for enabling digital twin functionality on a building facade and discusses advantages like cost savings and tenant comfort improvement. The research primarily focuses on the building facade, but it suggests future exploration into applying digital twins to building interiors. The idea of expanding the sensor network for enhanced applications, including security and movement monitoring, is also raised. Lastly, the study emphasizes the importance of evaluating the system's cost-effectiveness relative to its benefits.

- Reported energy efficiency improvements: Possibility for finer temperature and lighting control.
- Reported benefits: Lowering maintenance cost, lower management and operational cost.
- Reported quantitative improvements from DT: None
- Technology highlights: Bluetooth, WiFi, Python, CSV format.

Li et al. (2022) introduced a new solution to connect Digital Twins (DTs) with intelligent buildings by creating a foundational model for Building Digital Twins (BDTs). This model includes static information, a physical representation, and interaction mapping for virtual representation of physical buildings. The paper discusses sub-model characteristics, collaboration between models, real-time sensing, and feedback control. The proposed approach offers a platform-independent method for describing BDTs and ensures the foundation model's validity. A case study demonstrates real-time operation and maintenance using a chiller DT, validating the effectiveness of the model. However, the paper lacks in-depth technology implementation discussions and doesn't fully explore dynamic evolution. The presented case study is relatively simple, suggesting future work should focus on more complex systems to validate the model further.

- Reported energy efficiency improvements: Improve chiller's coefficient of performance (COP) by manipulating the chiller setpoints more intelligently.
- Reported benefits: Lower management and operational cost, less energy consumption.
- Reported quantitative improvements from DT: An increase in the chiller's COP of around 40% when optimization active.
- Technology highlights: IFC, WebGL, Python, Modbus.

Anomaly detection

Bjørnskov et al. (2022) introduced a systematic method for retro-commissioning, which emphasizes rectifying issues and irregularities in retrofitted facilities. The study uses a hospital in Odense, Denmark as a case example, showcasing a dynamic model-based solution to retro-commissioning various building components. This technique involves identifying faults by applying predetermined thresholds, revealing problems like improperly functioning cooling coils. Despite the increasing interest in retrofitting buildings, many countries still have gaps in retro-commissioning procedures. The approach recommended in the paper is adaptable and scalable, suitable for diverse building types and locations, necessitating minor adjustments to suit specific systems. The utilization of clamp-on sensors for data collection and calibration is a practical and widely applicable solution. Developing and fine-tuning a dynamic energy model marks the initial stages of implementing continuous commissioning within the BuildCOM (Jradi et al. 2021) research project.

- Reported energy efficiency improvements: Better energy models, provide a better baseline for measuring energy efficiency.

- Reported benefits: More realistic monitoring and forecasting of energy usage, more accurate detection of improper operation.
- Reported quantitative improvements from DT: None
- Technology highlights: EnergyPlus, Clamp-on sensors, WiFi & cellular internet.

Lu et al. (2020d) created a Digital Twin (DT)-enabled anomaly detection system to comprehensively monitor building assets during the operations and maintenance (O & M) phase. It introduces a novel DT-based anomaly detection process flow that integrates data, enhances decision-making, and automates the detection process. The study also designed a data integration structure based on IFC (ISO 2018) extension for diverse operational data management. The framework's efficacy was demonstrated through a case study involving HVAC system pumps, highlighting its ability to continuously monitor building assets and streamline daily O & M management.

- Reported energy efficiency improvements: None
- Reported benefits: More accurate and faster detection of improper operation.
- Reported quantitative improvements from DT: None.
- Technology highlights: IFC, BMS

Lu et al. (2020c) presented the development of a DT system architecture and presents a DT demonstrator for the West Cambridge site, focusing on a building-level DT. The challenges of DT development, particularly related to data management, are thoroughly analyzed, and lessons learned are discussed. The study offers a novel system architecture for future research, showcasing one of the early exploratory pilot projects for building and city-level DTs. It provides a road-map for future research while acknowledging the need for organized guidance to tackle data management challenges. The paper doesn't extensively cover the value of integrating city-level information, which is suggested as a topic for future research. The authors plan to collect occupant feedback, collaborate with the University of Cambridge's Estate Management Department, validate the system architecture on a broader city scale, and explore practical applications of DTs in diverse management activities and services.

- Reported energy efficiency improvements: None
- Reported benefits: Anomaly detection, maintenance optimization, support for decision-making
- Reported quantitative improvements from DT: None
- Technology highlights: IFC, cellular internet, radio frequency, cloud databases.

Operational optimization

Bjørnskov and Jradi (2023) introduced an energy modeling framework rooted in the SAREF (2023) ontology, emphasizing modular data-driven models. Using SAREF4BLDG (2020) and SAREF4SYST (Kukkonen et al. 2022) extensions, the framework links model inputs and outputs systematically. This foundation will be extended to real buildings, incorporating devices, sensors, and diverse services. Utilizing SAREF ontology enhances interoperability, integration with physical systems, and scalability of DTs, facilitating broader adoption across domains like industry, energy, and smart cities, potentially expanding to streets, districts, and cities. The study presents a use case focused on a room equipped with temperature and ventilation sensors and controls. It highlights how the python framework is applied in a service designed to detect anomalies in components.

- Reported energy efficiency improvements: None
- Reported benefits: Semantic modeling, anomaly detection, easily integrable and extensible.
- Reported quantitative improvements from DT: None.
- Technology highlights: Ontologies, Python, BMS and IFC.

Tagliabue et al. (2021) discussed the application of a digital twin for assessing sustainability using rating systems like LEED (Green Building Council 2023). The digital twin is utilized throughout an asset's lifecycle, including design and use phases. This solution improves building management and real-time sustainability evaluation compared to traditional checklist-based protocols. The eLUX building (Uni Brescia building 2016), a prototype in the University of Brescia, serves as a case study. Equipped with sensors, it collects and displays indoor environmental quality and occupancy data. The digital twin supports user behavior by showing a sustainability scoreboard, promoting sustainable actions. The text highlights limitations in using a Digital Twin (DT) for sustainability purposes, particularly in the creation of a Sustainable Digital Twin (SDT). The DT was originally designed with a focus on predictive maintenance, indoor air quality, space organization, and energy efficiency. Sustainability assessment was added later, causing challenges. The suggestion is to create an SDT specifically for sustainability, which could address these issues.

- Reported energy efficiency improvements: None
- Reported benefits: Near real-time assessment of building sustainability index.
- Reported quantitative improvements from DT: None
- Technology highlights: NoSQL database, ethernet local area network, BIM.

Clausen et al. (2021) introduced a Digital Twin Framework for implementing Model Predictive Control (MPC) in both physical and simulated buildings. The framework encompasses an architecture for building control, occupancy prediction, and data format using sMAP. It includes a parameterized Zone Model that can be adjusted for controllable zones and a Zone Control Application enabling temperature and CO2 target configuration. An instance of this framework was applied to control a university classroom (room U182) in SDU Odense, Denmark. The experiments showed that the system can keep comfort levels comparable to those of commercial control strategies while also allowing for energy-saving approaches. This involves a multi-objective optimization problem that balances comfort and energy conservation, such as adjusting variable air volume (VAV) damper positions based on occupancy predictions. This improved upon default rule-based strategies. However, due to complex factors like the building's ventilation system and weather fluctuations, quantifying energy savings precisely remains challenging.

- Reported energy efficiency improvements: Planning energy consumption based on grid behavior without compromising occupant comfort.
- Reported benefits: Potential for an increase in energy efficiency.
- Reported quantitative improvements from DT: None
- Technology highlights: Generic data layer, model predictive control, sMAP bus (Dawson-Haggerty et al. 2010).

Jradi and Bjørnskov (2023) presented a complementary paper of their earlier work (Bjørnskov and Jradi 2023), it introduces a comprehensive digital twin platform designed to enhance the energy efficiency and intelligence of buildings. The platform integrates dynamic data-driven energy models with real-time data from various sensors and meters within the building. It replaces traditional Building Information Models (BIMs) with dynamic energy models combined with real-time data. The platform provides several key services:

The platform gathers and manages data from various sources within the building, creating a user-friendly open-standard context information model. It offers real-time tracking, continuous commissioning, and fault detection for effective energy management and rapid issue identification. Additionally, it supports optimal decision-making through simulations, enabling informed choices and alternate control strategies for the building's lifecycle.

- Reported energy efficiency improvements: None
- Reported benefits: More accurate, easier to create an maintain models for DTs.
- Reported quantitative improvements from DT: None
- Technology highlights: Python, building management systems.

Lee et al. (2016) discussed the use of Building Information Modeling (BIM) and various technologies to enhance building energy efficiency. The focus is on using devices like sensors, digital meters, and integrated platforms to automate energy-saving actions. The paper proposes employing a manager with basic knowledge to oversee these systems in a centralized Energy Operation Center (EOC) to reduce management costs. BIM is highlighted as a tool for visualizing building equipment data, aiding monitoring, and facilitating smart city management. A case study is presented, showing how this approach improves energy efficiency by managing the EOC and integrating various technologies. It is estimated that using BIM-based energy efficiency methods could lead to significant energy savings in Sejong City's (South Korea) buildings. The paper concludes that this solution can optimize building energy performance, reduce costs, and minimize environmental impact. The ultimate aim is to develop a control unit for a smart city's energy grid system using the building energy integrated operation center.

- Reported energy efficiency improvements: Finer and automated control of lighting, HVAC and electronic equipment results in a better resource management.
- Reported benefits: Energy consumption reduced, constant monitoring and anomaly detection a centralized control interface for the building's systems

- Reported quantitative improvements from DT: 17% energy reduction.
- Technology highlights: BACnet, BIM, wireless sensor networks (WSN).

Moretti et al. (2020) introduced an openBIM methodology aimed at aiding dynamic Asset Management (AM) applications even when there is limited available as-built information. The approach utilizes the IfcSharedFacilitiesElements schema for processing both existing and newly created Industry Foundation Classes (IFC) objects, allowing real-time integration of data. The methodology is tested using data from the West Cambridge DT Research Facility, demonstrating its potential for supporting asset anomaly detection. By integrating BIM and IoT tools, this solution enhances the automation of digital AM processes within the context of building development. The method proves effective for existing buildings, addressing issues related to data scarcity. It enables easier access to data across domains, supporting the creation of AM applications for intelligent buildings. This approach facilitates both the integration of static AM data and real-time IoT data, reducing uncertainty and automating operations. The study showcases the openBIM solution's potential in built Asset Management and suggests testing its robustness through additional application case studies in future research.

- Reported energy efficiency improvements: None
- Reported benefits: A standard approach to implement DTs for buildings with a scarcity of data. Effective utilization of BIM data and sensor data in a unified IFC-based system.
- Reported quantitative improvements from DT: None
- Technology highlights: WSN, BIM, BMS, language-agnostic UML specification.

Peng et al. (2020) discussed an exemplary Digital Twin (DT) project conducted at East Hospital for over a year. The project aimed to achieve improved performance and energy efficiency through continuous lifecycle integration. The results showed a 10% increase in management satisfaction, approximately 1% energy savings annually, and over 10% avoidance of facility faults and repairs through DT diagnosis. While the case was specific to Shanghai, China, the solution has wider applicability to modern hospitals globally due to shared management needs and electrical systems.

The paper emphasizes three key points: Continuous Life-cycle Integration, Real-time Visual Management and Intelligent DT Diagnosis. However, the implementation revealed certain shortcomings and challenges: Professional System Integration, Financial Risks and Data Security and Ownership.

- Reported energy efficiency improvements: An automated pattern recognition algorithm finds what is the normal usage of electric equipment and notifies workers when abnormal behaviour is found, asking them to intervene to reduce energy waste.
- Reported benefits: A unified visualization and control digital system for the building increased the operation and management satisfaction. Fault prediction and validation allowed for less maintenance costs.
- Reported quantitative improvements from DT: Around 1% increase in energy efficiency.

- Technology highlights: BacNet, OPC and HTTP API requests. Apache kafka and private cloud storage.

Wang et al. (2022) introduced the concept of using digital twin technology in building operation and maintenance processes, along with the integration of machine learning algorithms for intelligent prediction. The process involves establishing a digital twin model for building operation and maintenance, integrating and visually displaying relevant data. The machine learning algorithm is then applied for data-driven predictions and diagnoses.

The paper highlights 3 main key points: A framework is proposed for digital twin tech in building operation and maintenance combined with machine learning for intelligent predictions and diagnoses. The digital twin tech aids in visualizing and retrieving diverse operational data. 3D model-based data retrieval is more intuitive than traditional methods. The potential for achieving intelligent building operation and maintenance is emphasized.

- Reported energy efficiency improvements: None
- Reported benefits: A framework and DT development process that allows for fast integration with artificial neural networks (ANN).
- Reported quantitative improvements from DT: None
- Technology highlights: BIM, ANN.

Zaballos et al. (2020) suggested a Smart Campus (SC) concept involving the integration of Building Information Modeling (BIM) and IoT-based wireless sensor networks (WSN) for environmental monitoring and emotion detection. This aims to gauge occupants' comfort levels, which significantly impact productivity. The research is conducted within the software environment of Autodesk Revit (2023b) 2020, combining BIM and IoT to provide real-time access to information and automation.

SC supports intelligent decision-making processes, energy efficiency, and comfort. The model encompasses three intelligence domains: Green campus (energy consumption), Healthy campus (comfort monitoring), and real-time facility management. The ongoing research project aims to develop a multi-disciplinary Smart Campus with distinctive characteristics to enhance sustainability beyond traditional campuses.

- Reported energy efficiency improvements: None
- Reported benefits: Enhanced comfort enabled through real-time environment monitoring and emotion-detection.
- Reported quantitative improvements from DT: None
- Technology highlights: BIM, WSN, bluetooth, arduino, ethernet, WiFi.

Zhao et al. (2022) employed illustrative case studies to explore how DTs are used in FM, leading to improved building performance and enhanced efficiency of Mechanical, Electrical, and Plumbing (MEP) systems. The study highlights real-time data collection, predictive maintenance, and cost reduction as key benefits of DT implementation. A conceptual framework is developed to address challenges in integrating Building Information Modeling (BIM) and FM models, providing guidance for implementing DT with considerations for data acquisition, processing, modeling, and application. The use of Machine Learning (ML) and Artificial Intelligence (AI) in DT is proposed to enhance FM systems' intelligence and communication. The research's findings contribute to practitioners' understanding of DT's impact on FM and suggest a content-dependent approach to knowledge development. Overall, the study underscores DT's potential to transform FM practices in the digital construction era, proposing solutions to implementation challenges.

- Reported energy efficiency improvements: None
- Reported benefits: A standard abstraction of a digital twin for buildings.
- Reported quantitative improvements from DT: None
- Technology highlights: BIM

Agostinelli et al. (2022) focused on a policy for digitizing port infrastructure to enhance maintenance processes and energy efficiency, ultimately transitioning port areas into Zero Energy Districts (ZED). The Lazio Region initiated this process in 2020, with the Anzio port serving as a representative pilot project due to its relevance in the Mediterranean context. The study's objective was to establish energy-saving strategies and incorporate Renewable Energy Systems (RESs) to promote sustainable mobility. The paper elaborates on these strategies, conducts an energy analysis starting from the current state, and showcases the potential for the infrastructure to achieve energy self-sufficiency. The concept of utilizing a Digital Twin (DT) for the area's analysis is highlighted. Moreover, the text discusses the synergistic benefits of integrating Building Information Modeling (BIM) and Geographic Information System (GIS) techniques to maximize the impact of energy efficiency measures.

- Reported energy efficiency improvements: A detailed energy model provided insights into the major consumers of energy in the port, replacing the lighting to LED technology reduced drastically the total energy consumption.
- Reported benefits: Reduced energy consumption, a decision-making tool in the form of a digital model with aggregated BIM and GIS data, providing insights into solar and wind potential.
- Reported quantitative improvements from DT: Around 15% of total energy consumption reduction after the structural changes.
- Technology highlights: BIM, GIS, Autodesk Revit.

Predictive maintenance

Hosamo et al. (2022) discussed the application of Digital Twin technology in facilitating predictive maintenance and dynamic maintenance strategies in the Facility Management and Maintenance (FMM) process. The proposed framework involves integrating data from Building Information Models (BIM), Internet of Things (IoT) sensor networks, and Facility Management (FM) systems. The framework includes three modules for predictive maintenance: operational fault detection, condition prediction, and maintenance planning. Various machine learning techniques like Artificial Neural Networks (ANN), Support Vector Machines (SVM), and decision trees are used to predict the state of components and enhance the lifetime of Air Handling Unit (AHU) components.

The research proves that automated fault detection in Air Handling Units (AHUs) is highly effective, performing well with different AHU types and problems. The paper covers data sources, semantic data definitions, and techniques for identifying and fixing faults.

Nevertheless, the paper recognizes certain drawbacks. The accuracy of predictions is influenced by developers' algorithm choices, tied to their expertise. The study emphasizes the importance of exploring alternative prediction methods. Future directions include adopting an ontology-based solution for consistent integration of data from diverse sensors and systems. The paper suggests using incremental learning techniques to regularly enhance the prediction models with new input data.

- Reported energy efficiency improvements: None.
- Reported benefits: Cost reduction through predictive maintenance of ventilation systems.
- Reported quantitative improvements from DT: None.
- Technology highlights: IFC, Ontologies, Web API, Autodesk Revit. RS 485 sensors, TCP/IP enabled.

Ni et al. (2021) introduced a cloud-based framework for digitizing historic buildings through digital twins and AI development. The framework has been applied to three chosen historic buildings, demonstrating successful collection, transmission, and storage of data in the cloud. This allows the creation of digital twins updated with real-time sensor data. Future plans involve installing sensor boxes in these buildings to extract valuable insights from the collected data. This will enable the creation of AI models for tasks like anomaly detection, occupancy prediction, and energy-efficient control, contributing to building preservation and energy optimization.

In another study, Ni et al. (2022) extended their work to enhance (Ni et al. 2021). This study aimed to enhance the preservation of historic buildings by utilizing digitalisation methods to create digital twins. By combining Internet of Things (IoT) technology and ontology, the study proposed a solution to consistently represent data from historic buildings, showcase their current operational state, and enable further data analysis. The study developed an IoT system using hardware, open-source software libraries, RealEstateCore ontology, and Microsoft Azure to implement this solution. A practical case study conducted in a historic building demonstrated that a digital twin reflecting the building's real-time status can be generated using sensor data. Insights from the digital twin were used to improve the indoor environment of the building for both heritage preservation and human comfort. Future work could involve using monitored indoor conditions to estimate occupancy levels and incorporating additional data, such as energy consumption, to model energy behavior and reduce operational costs of historic buildings.

- Reported energy efficiency improvements: None
- Reported benefits: Real-time monitoring, an unified knowledge-base of the building, possibility to do data analytics.
- Reported quantitative improvements from DT: None, however presented an estimated cost for cloud services of 3000 Swedish crowns for 100 data entry points.
- Technology highlights: Arduino, cellular internet, Azure cloud, ontologies.

Simulation of alternative scenarios

Agostinelli et al. (2021) discussed the implementation of Digital Twin (DT) methodology in buildings, enabling them to enhance their knowledge using sensor data and integrate with AI systems for self-learning and prediction. The research's main goal is to use machine learning to manage self-production and supply systems in an energy smart grid, addressing thermal and electrical loads. Real-time monitoring through DT improves building energy performance, identifying user behaviors and refining energy strategies. Load forecasting allows to simulate and predict daily thermal loads using historical sensor data and smart metering, while optimizing energy balance and production systems. The DT also optimizes indoor comfort by adjusting system operations based on environmental data. Extending the research to urban contexts, the integration of BIM-GIS systems aids in connecting urban energy cells to the national grid, focusing on electric mobility and storage.

- Reported energy efficiency improvements: Using solar and geothermal power sources, orchestrated by a digital twin platform, the energy demand from the grid was significantly reduced.
- Reported benefits: Cost reduction from energy optimizations.
- Reported quantitative improvements from DT: Around 38% cost reduction from energy consumption.
- Technology highlights: Bluetooth, WiFi, BIM, GIS, Autodesk Revit

Kaewunruen and Lian (2019) introduced a 6D Building Information Model (BIM) for a railway turnout system. This BIM system covers all stages from planning to demolition, providing comprehensive project information. A life-cycle assessment was also conducted using shared information. The BIM acts as a data-sharing platform, improving planning efficiency, collaboration, and sustainability. It enhances maintenance visualization, stakeholder collaboration, and cost estimation. The digital twin aspect aids stakeholders in policy and sustainability solutions. The study demonstrates BIM's role in promoting cleaner production and maintenance policies. With evolving technology like 'Internet plus', BIM is expected to integrate with GIS for various applications in urban planning, triggering a digital revolution in engineering construction towards innovation. It is worth nothing that this is the only author in this review who does not differentiate between BIM and Digital Twin concepts.

- Reported energy efficiency improvements: None
- Reported benefits: BIM implementation can reduce capital cost and carbon emissions by allowing prioritisation of maintenance and operational works.
- Reported quantitative improvements from DT: None.
- Technology highlights: BIM, GIS, no data collection in site.

Table 3 presents a non-exhaustive summary of the reported benefits of the digital twin use cases, with special attention to the reported achievements related to energy efficiency. As it can be appreciated, only 5 out of 20 analyzed use-cases reported any sort of quantitative benefits. The majority of the studies restrain from reporting the total cost reduction or improvement of energy efficiency resulting from the DT implementation.

Table 3 Summary of the reported benefits of DT, with special emphasis in energy efficiency

Study	Energy efficiency benefits	Other benefits	Reported quantitative benefits
Khajavi et al. (2019)	Finer temperature and lighting control	Lower costs	None
Li et al. (2022)	Improve chiller's COP	Lower costs Lower energy consumption	40% COP increase
Bjørnskov et al. (2022)	Better baseline energy models	More realistic monitoring and detection	None
Lu et al. (2020d)	None	Detection of improper operation	None
Lu et al. (2020c)	None	Detection of improper operation	None
Bjørnskov and Jradi (2023)	None	Semantic modeling	None
Chiara Tagliabue et al. (2021)	None	Sustainability assessment	None
Clausen et al. (2021)	Planned energy consumption	Potential increase in energy efficiency	None
Jradi and Bjørnskov (2023)	None	More accurate, easier to maintain models	None
Lee et al. (2016)	Finer temperature and lighting control	Lower costs Constant monitoring	17% Energy consumption reduction
Moretti et al. (2020)	None	Unified IFC-based system	None
Peng et al. (2020)	Optimization recommendations	Unified visualization and control	1% Energy consumption reduction
Wang et al. (2022)	None	DT framework for using ANNs	None
Zaballos et al. (2020)	None	Enhanced comfort	None
Zhao et al. (2022)	None	Standard conceptual model for DTs	None
Agostinelli et al. (2022)	Energy model to support decision-making	Integrate BIM and GIS for better decisions	15% energy reduction after retrofitting
Hosamo et al. (2022)	None	Lower costs Predictive maintenance	None
Ni et al. (2021)	None	Real-time monitoring	None
Agostinelli et al. (2021)	Renewable sources orchestration through DT	Lower costs	38% cost reduction from retrofitting+DT
Kaewunruen and Lian (2019)	None	Lower costs	None

Commercial tools for digital twins for buildings

A thorough review of existing literature has been conducted to highlight the substantial potential of digital twin technology across a range of applications in building operation. In addition to the theoretical and experimental investigations reviewed above, this section will present the commercial tools presented and developed in recent years to deliver various services of digital twins in buildings. These tools come predominantly from firms specializing in energy, engineering, and construction. A detailed review of these recent instruments is presented:

- Arup has created 'Neuron' (Arup 2023a), an intelligent digital twin system for buildings, aimed at aiding property owners in attaining notable energy conservation via sophisticated machine learning and anticipatory upkeep. This system employs 5 G and the Internet of Things (IoT) to collect up-to-the-minute sensory data from various equipment and systems. Furthermore, it utilizes Building Information Modelling (BIM) to exhibit these intricate datasets via a cloud-centric, unified administrative interface. Additionally, Arup harnesses artificial intelligence and machine learning to assess, enhance, and mechanize operations.
- Granlund introduced a platform showcasing the Granlund Manager's Digital Twin (Grandlund 2023), which conveniently displays data in real-time, superimposed on the building's three-dimensional layout. This enables the tracking of conditions on a building-wide, floor-specific, and individual unit level. The Digital Twin amalgamates information from Building Information Models (BIMs) utilized during the planning stage, along with data from Internet of Things (IoT) and automation systems, as well as insights from property occupants, among other origins.
- Autodesk has introduced 'Autodesk Tandem' (Autodesk 2023a), a cloud-based digital twin platform designed for building and facility applications. This technology allows projects to remain digital from inception to completion by utilizing Building Information Modeling (BIM) data. With Autodesk Tandem, construction and engineering companies can create and deliver a digital twin to building owners, providing them with accessible, contextual, and insightful data for seamless operations. The Tandem platform empowers architectural, engineering, and construction (AEC) firms to utilize BIM data throughout the project lifecycle, facilitating the creation and delivery of a digital twin. Moreover, it assists owners in integrating operational systems with the digital twin to convert fragmented data into actionable business intelligence.
- Siemens presented the 'Building Twin' (Siemens 2023), a digital twin solution that offers real-time insights into a building's performance, allowing instant modifications to enhance efficiency and furnish data for refining the design of upcoming buildings. The suggested digital twin contributes to more economical, uncomplicated, and environmentally conscious smart buildings. These advantages are realized through improved comprehension of building performance, swift detection and resolution of issues in real-time, and enhanced utilization of available space.
- Bosch has recently introduced its "Connecting Building Services" (Bosch 2023) package, employing Azure Digital Twins to develop solutions that are sensitive to the building's context. This involves crafting digital depictions of assets, surroundings, and business systems within buildings and facilities. This capability empowers clients

to utilize predictions and anticipatory insights, leading to quicker, more knowledgeable choices in enhancing building efficiency and minimizing carbon emissions.

- Catenda has developed a digital platform solution, named 'Bimsync Arena' (Catenda 2023b) as part of their newly developed Catenda Hub, designed to enhance the creation of building digital twins. This platform facilitates improved design collaboration, error reduction, time savings, and elevated deliverable quality, all powered by an open BIM collaboration environment. Bimsync (Catenda 2023a) seamlessly connects information and data to the virtual asset through an intuitive interface, ultimately culminating in the creation of a comprehensive building digital twin.

Classification based on the data integration level

Table 4 presents a consolidated analysis of the case studies examined. This analysis specifically focuses on the integration of data within the digital twin implementations, as per the classification framework proposed by Kritzinger et al. (2018), as shown in Fig. 6. Notably, several articles describe a comprehensive digital twin framework or development process that includes extensive data integration. However, in order to analyse the experience obtained from each real-life system, only the implemented use cases from each study are considered.

Table 4 Data integration level for the analyzed use cases

Study	Domain	Level of integration	BIM	ML	Models' type
Khajavi et al. (2019)	Component monitoring	Digital shadow	✓		Sensor data only
Li et al. (2022)	Component monitoring	Digital twin	✓		Gray-box
Bjørnskov et al. (2022)	Fault detection and commissioning	Digital model			White-box
Lu et al. (2020d)	Fault detection and commissioning	Digital shadow	✓		Gray-box
Lu et al. (2020c)	Fault detection and commissioning	Digital shadow	✓	✓	Gray-box
Bjørnskov and Jradi (2023)	Operational optimization	Digital shadow		✓	Gray-box
Chiara Tagliabue et al. (2021)	Operational optimization	Digital twin	✓	✓	Gray-box
Clausen et al. (2021)	Operational optimization	Digital twin			Gray-box
Jradi and Bjørnskov (2023)	Operational optimization	Digital shadow	✓		Gray-box
Lee et al. (2016)	Operational optimization	Digital shadow	✓		Sensor data only
Moretti et al. (2020)	Operational optimization	Digital shadow	✓		Sensor data only
Peng et al. (2020)	Operational optimization	Digital shadow	✓	✓	Gray-box
Wang et al. (2022)	Operational optimization	Digital shadow	✓	✓	Gray-box
Zaballos et al. (2020)	Operational optimization	Digital shadow	✓		Gray-box
Zhao et al. (2022)	Operational optimization	Digital model	✓		Sensor data only
Agostinelli et al. (2022)	Operational optimization	Digital model	✓		White-box
Hosamo et al. (2022)	Predictive maintenance	Digital shadow	✓	✓	Gray-box
Ni et al. (2022)	Predictive maintenance	Digital shadow		✓	Gray-box
Ni et al. (2021)	Predictive maintenance	Digital shadow			Sensor data only
Agostinelli et al. (2021)	Scenario simulation	Digital shadow	✓	✓	Gray-box
Kaewunruen and Lian (2019)	Scenario simulation	Digital model	✓		White-box

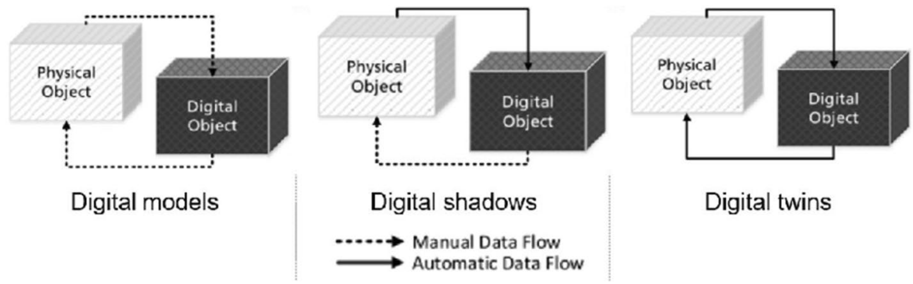

Fig. 6 Levels of data integration for digital twins (Kritzinger et al. 2018)

Table 5 Data integration level for the analyzed commercial tools

Tool	Level of integration	BIM	ML
Arup (2023a) Arup Neuron	Digital shadow	✓	✓
Grandlund (2023) Grandlund Manager's Digital Twin	Digital shadow	✓	
Autodesk (2023a) Autodesk Tandem	Digital shadow	✓	
Siemens (2023) Siemens Building Twin	Digital shadow	✓	
Bosch (2023) Bosch Connecting Building Services	Digital shadow		
Catenda (2023a) Catenda Hub	Digital shadow	✓	

In the 'Models Type' column, an endeavor is made to classify the mathematical and physical models employed for simulation, estimation, and forecasting within each case study. In instances where no specific models for these purposes are identified, and the digital twin services rely solely on sensor inputs, such scenarios are categorized as 'Sensor Data Only'. The classification further delineates whether the models used are exclusively physical (termed 'White-Box'), solely statistical ('Black-Box'), or a hybrid of physical and statistical approaches ('Gray-Box'). For instance, a system leveraging sensor data to calibrate parameters within a physics-based model would be categorized as a 'Gray-Box' model.

Following the guidelines described in "Classification based on the data integration level" section, Table 4 compiles the classification of the use cases analyzed. As appreciated in the table, the vast majority of digital twin for building solutions use BIM as part of the creation process of the DT. There is only one study where the BIM model is created as part of the DT creation process (Peng et al. 2020) while all the other BIM uses attempt to utilize a previously existing model.

This analysis reveals a trend in the modeling approaches for simulation and forecasting in digital twin services. Selected studies (Khajavi et al. 2019; Lee et al. 2016; Moretti et al. 2020; Zhao et al. 2022) integrate only sensor data with preprocessing techniques to inform building management, without mathematical processing of this data. Conversely, the predominant modeling solution for estimating key digital twin metrics relies on Gray-Box methods. These methods synergize physical laws and statistical techniques, offering a range of digital twin services based in forecasting and simulation.

In the case of the enterprise solutions, a classification of each one of the presented solutions is depicted in Table 5:

Given that enterprise solutions typically provide a centralized source of truth with real time data ingestion from the building they are classified as digital shadows following the previously mentioned classification, this is further discussed in "Commercial tools vs custom implementations" section.

Discussion

Consensus on digital twin definition

The analysis evidences the lack of consensus on the definition of Digital Twins. For instance, some studies using an isolated digital simulation refer to their solution as digital twin. A more granular segmentation can be useful to understand the different levels of maturity of the digital twin implementations. Utilizing the levels of data integration of Kritzinger et al. (2018) for digital twins in manufacturing, as shown in Fig. 6, enables a more detailed description of the level of data integration among the analyzed use cases, as is evident in Table 4. The number of case studies with complete feedback loops, sensor data and some sort of automated action occurring in the building is relatively small, all the documents use the term *digital twin* to refer to their implementation.

In addition, the term "digital twin" is interpreted in various ways, particularly in its simulation and predictive functions. Many academic studies define digital twins as models of physical assets with the ability to simulate scenarios, a considerable number of the reviewed academic studies agree on the simulation function of digital twins. On the contrary, commercial tools commonly define a digital twin as a centralized platform for visualizing sensor data and operational information. These commercial definitions do not always include simulation abilities or models based on physical laws. This distinction highlights the different emphasis placed on digital twins by academic research versus commercial applications.

Digital twins' relation to energy information systems (EIS)

Building Energy Information Systems (EIS) are specialized platforms designed to monitor, analyze, and control the energy use of buildings (Granderson et al. 2011). They collect data from various sources, such as HVAC systems, lighting, and other energy-consuming devices, to provide insights into the building's energy performance. EIS tools help in identifying inefficiencies, optimizing energy use, and reducing operational costs. They can also support decision-making processes for energy conservation measures.

On the other hand, a digital twin for buildings is a virtual model of a physical building. It integrates data from various sources, including sensors, systems, and external data feeds, to create a real-time, dynamic representation of the building. This model can simulate, predict, and analyze the building's performance under various conditions. The points below address the relationship and integration potential between EIS and digital twins:

> Enhanced Data Integration and Analysis: Digital twins can enhance the capabilities of EIS by providing a more detailed and comprehensive model of the building. Digital twins can simulate the impact of different energy conservation measures, helping stakeholders make more informed decisions.

Real-time Performance Optimization: By integrating EIS with digital twins, buildings can achieve real-time energy performance optimization. The digital twin can simulate various scenarios in real-time, allowing the EIS to adjust systems to improve energy efficiency dynamically.
Sustainability and Compliance: Digital twins, through their detailed simulation capabilities, can help buildings comply with energy regulations and standards by accurately predicting and demonstrating energy performance. When combined with EIS, buildings can not only monitor compliance but also find innovative ways to improve sustainability metrics.

In conclusion, digital twins for buildings and Building Energy Information Systems (EIS) are intricately linked technologies. When combined, they can greatly improve how we manage, operate, and optimize energy use within buildings. While digital twins offer a broader perspective that might not always concentrate on energy systems, their integration with the data-driven and energy-focused approach of EIS holds significant promise. This combination brings together the detailed modeling and predictive capabilities of digital twins with the monitoring and operational strengths of EIS.

Commercial tools vs custom implementations

Commercial tools' strength relies mainly in the ease of use, solution's like Arup's "Neuron" (Arup 2023a), Siemens' "Building Twin" (Siemens 2023) and Autodesk Tandem (Autodesk 2023a) offer a comprehensive suite of visualization tools and provide the users with the possibility of implementing dashboards. They also integrate with the most popular digital systems and protocols, such as BMS systems, BACNet and Modbus protocols.

Table 6 presents a different angle for the analysis of the commercial tools, providing a direct comparison of the potential services offered by these tools and the custom-made studies analysed. The services provided by commercial tools are usually an extension of BIM technology to incorporate sensor measurements (Arup 2023a; Siemens 2023; Autodesk 2023a; Catenda 2023b). This system architecture allows typically for monitoring, anomaly assessment and enhanced operation, based on the same monitoring capabilities and manual action-taking. However, they lack any sort of physical model which simulates the building systems and therefore any forecasting or predictive maintenance capability is generally not available.

Table 6 Supported topics from each commercial tool, based on publicly available descriptions of the tools

Theme	Tools
1. Component monitoring	Neuron, Granlund, Autodesk Tandem, Building Twin, Bosch DT service, Bimsync Arena
2. Anomaly detection	Neuron, Autodesk Tandem, Building Twin, Bosch DT service, Bimsync Arena
3. Operational Optimization	Neuron, Granlund, Autodesk Tandem, Bosch DT service
4. Predictive maintenance	(None)
5. Simulation of alternative scenarios	(None)

It is worth noting that the commercial solutions focus on providing data services and dashboards for building operators which then can take actions based on the unified source of information. If an automatic controlling action is desired, custom integration or expansions of the solution would be necessary. Enabling a full duplex digital twin solution would require extra steps tailor made for each specific scenario.

Enterprise solutions still enable many of the benefits of having digital twins in the built environment, such as real-time monitoring and diagnosis. Decision-making support and the possibility of forecasting and enhancing the energy efficiency throughout the building.

In contrast, custom digital twin solutions are tailored to address the specific operational needs of each building. These systems offer detailed insights and possess the flexibility required for the implementation and iterative development of the digital twin, facilitating its continuous evolution. Over time, these solutions can be fine-tuned to emphasize operational benefits that yield the most significant impact, and can integrate advanced features like automation and control loops for building systems. However, the development and maintenance of custom solutions necessitates a dedicated team of engineers and specialists, often resulting in higher costs compared to standard off-the-shelf products. Additionally, while custom digital twins are designed for expert users, this focus can limit their accessibility and usability for external stakeholders who may not have in-depth knowledge of the system.

Digital twins for energy efficiency

Table 3 suggests that digital twins can enhance energy efficiency during the operation and maintenance phases of buildings. However, there is a lack of direct studies quantifying this impact, with only a few reported instances of measurable improvements. Notable among these are increases of up to 40% in the Coefficient of Performance (COP) for chillers, energy consumption reductions of 17%, and 15% reductions post-retrofitting. Retrofitting emerges as a key factor for improving energy efficiency, which may necessitate additional investment in the building's physical systems overhaul.

Additional potential advantages include:

- Cost Reduction: While several studies point to cost savings as a major benefit of digital twins, quantitative evidence backing these claims is sporadic.
- Operational Improvements: Digital twins offer more than just direct energy savings. They support enhanced operations through ongoing monitoring, identifying incorrect operations, and real-time surveillance, all of which may indirectly contribute to energy conservation.

Digital twins can contribute to energy savings in buildings through a variety of mechanisms. By creating a virtual replica of a building, digital twins enable the fine-tuning of temperature and lighting according to the patterns and behaviors of occupants, ensuring that energy is used optimally and only when necessary. They also empower building operators with data-driven recommendations on how to best manage and adjust the building's energy systems for maximum efficiency. Additionally, digital twins facilitate the simulation of various retrofitting scenarios, allowing stakeholders to assess the potential impacts and benefits before physical changes are made. This predictive capability not only aids in identifying the most effective retrofitting strategies but also minimizes the risks and costs associated with the trial-and-error of physical modifications.

In summary, digital twins hold potential for increasing energy efficiency and cutting costs in the building industry. Yet, the extent of these benefits is not consistently documented and varies greatly. The capacity to customize building operations and the provision of actionable insights demonstrate the strategic value of digital twins in optimizing energy use and enhancing overall building performance.

Challenges

A critical aspect shared by both custom and off-the-shelf digital twin solutions is their dependency on a robust data acquisition system. This system typically comprises a communications network and an array of sensors strategically distributed throughout the building. The efficacy of these solutions is contingent on the availability and quality of data gathered from these systems. A notable challenge arises when these systems need to be integrated with a Building Management System (BMS) present in the building. This integration often presents complexities that demand specialized engineering expertise to address effectively.

Additionally, most current digital twin solutions primarily depend on the use of Building Information Modeling (BIM), which, are not widely available for the majority of existing building stock (Volk et al. 2013). This gap signifies that digital twin solutions capable of integrating BIM data, yet not solely dependent on these models, are of significant interest. Such solutions would offer greater applicability and flexibility, especially in scenarios where comprehensive BIM data is unavailable or incomplete.

There is an emphasized need to compare different digital twin methods and define clear criteria for them. A consensus on the definition and scope of digital twins in construction and energy efficiency is missing. Therefore, further research is required to specify the optimal characteristics and proper boundaries of digital twins for building applications.

Proposed digital twin for building operation framework

Unlike in manufacturing, where digital twins often include a 3D model of the physical asset, digital twins for buildings may not always need this type of visualization. The setup of these digital twins can differ greatly, customized to meet the particular goals of the services they support. This means the intended use of the digital twin dictates its design, development, and implementation. For example, a digital twin designed for ongoing commissioning services would have a different configuration than one used for optimizing performance or analyzing retrofit options. Another example is the digital twin solution highlighted by (Lu et al. 2020c) which offers an interactive 3D visualization that can display indoor comfort metrics on demand. This functionality necessitates the use of 3D engines, robust systems for data transmission and integration, and sophisticated visualization dashboards. In contrast, Hosamo et al. (2022) describe a digital twin developed to facilitate predictive maintenance for Air Handling Units. This system merges building information with sensor data to run simulations and leverages machine learning to suggest maintenance schedules, indicating that digital twin solutions for buildings can significantly differ. Despite this variety, the fundamental architecture of digital twin models remains consistent, incorporating three essential layers common to all examined solutions. The abstraction of this layered model is depicted in Fig. 7.

These service-oriented digital twin solutions integrate one or many components in each layer. With an up-to-down design phase and an down to up implementation. The shape of the solution will be defined by the service is expected to provide. On this basis, the digital twins can be divided into three layers, Data, Model and Service layers.

- The Data Layer presents significant technical complexities within the digital twin framework. It involves the collection, integration, and transmission of data across various subsystems. The primary challenges at this level include ensuring high-quality data-particularly from Building Information Modeling (BIM) and sensors-and the integration of existing systems such as Building Management Systems (BMS), Geographic Information Systems (GIS), and online weather services.
- The Model Layer leverages the collected data together with user-defined models to produce specific outcomes. These may include simulation results, predictive forecasts, or optimization strategies derived from reasoning systems. Enhancing this layer's effectiveness often involves incorporating domain-specific knowledge and expert input to guide the modeling process.

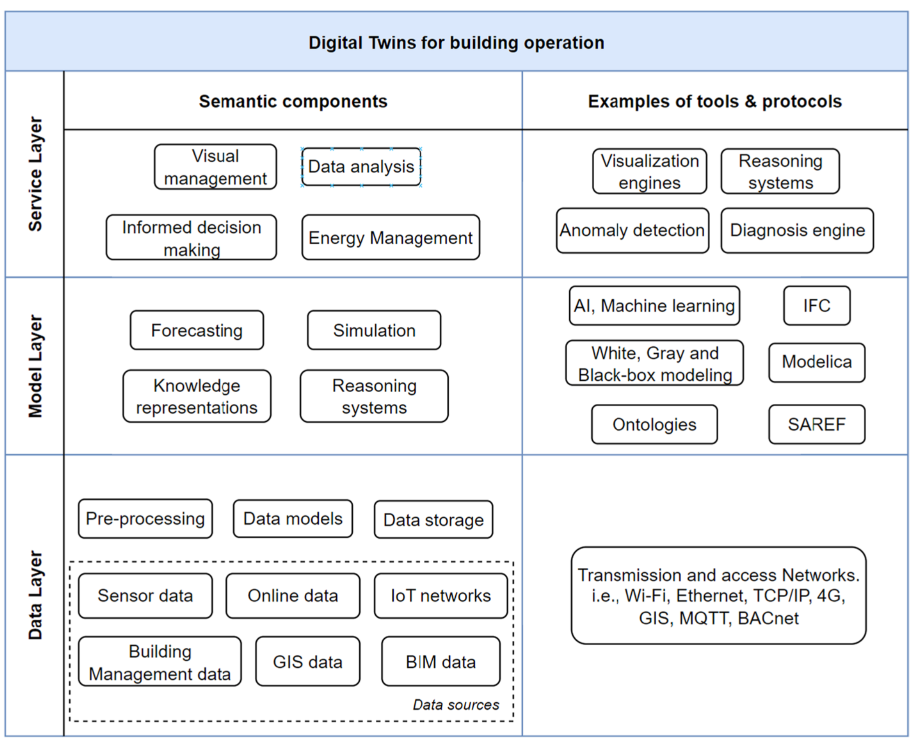

Fig. 7 Proposed Digital twin layer model with its different components as a basis for building operation and management support

- The service layer, deals with the implementation of the interface that will provide the end user with all the relevant information that will allow them to benefit from the digital twin. This layer can manifest as a user interface for data interaction or as part of an automated feedback loop where modeling outcomes directly influence the building's operation through actuators.

In line with the proposed digital model, the University of Southern Denmark together with public and private sector partners have launched the DanRETWin (Jradi et al. 2023) project, which aims to provide digital twin-based solutions for supporting and enhancing the retrofitting process of the danish building stock. Within the context of this project some of the mentioned challenges and future research efforts are going to be addressed. Integration and generalization of models in relation with old buildings, where digital information is very low or non-existing is one of the main research objectives.

Conclusions

This study evaluated the application of digital twins during the operational phase of building management. Integrating real-time data with digital models of buildings and their components enables services that include anomaly detection, continuous system monitoring, and energy use optimization. These services contribute to cost savings and improved building performance.

Digital twins have the potential to enhance energy efficiency and reduce operational costs in the building industry. They enable customization of building operations and provide operators with actionable insights, highlighting the strategic role of digital twins in optimizing energy consumption and bolstering overall building efficacy. However, the extent of these advantages is not consistently documented and exhibits considerable variability. Moreover, there is a notable lack of discussion on the costs involved in developing and maintaining digital twins relative to their quantifiable advantages.

The digital twin use cases reviewed predominantly rely on Building Information Modeling (BIM) for establishing the digital representation. Some studies detail the creation of a BIM model, which is subsequently integrated into a digital twin framework during the development phase of the digital twin.

A prominent obstacle in the rapid and effective development of building digital twins is the generally substandard quality of existing models and data. This challenge is exacerbated by the substantial effort required to synthesize various building systems and data processing technologies.

Digital twins in the construction sector are more inclined to offer service-oriented applications rather than exhaustive simulations of entire buildings and their subsystems. The specific purpose of a digital twin influences its design, development, and deployment. Consequently, there is no standardized architecture or set list of services for digital twins in building operations, leading to significant variations in the features of each digital twin based on its initial design and intended function.

Future work

Future research should aim to devise methods that do not exclusively depend on BIM data, and when BIM is utilized, to automate the extraction of model data. Further exploration into artificial intelligence and machine learning is warranted to refine digital twin applications, address integration complexities, and reduce the cost and time associated with their deployment. Concurrently, new studies on digital twins for buildings should pay special attention to the measurable benefits obtained from the digital twin, providing a reliable assessment of their value. This would involve a detailed analysis of the costs and savings over the lifecycle of the digital twin, ensuring that the economic and environmental implications are clearly understood and effectively communicated. These research areas are crucial for overcoming existing barriers and enhancing the practical deployment and effectiveness of digital twins in the industry.

Abbreviations

O&M	Operation and Maintenance
IoT	Internet of Things
BIM	Building Information Modeling
EU	European Union
DT	Digital Twin
IEA	International Energy Agency
AI	Artificial intelligence
AEC	Architecture, Engineering, Construction
ML	Machine Learning
BDT	Building digital twin
HVAC	Heating, Ventilation and Air conditioning
LEED	Leadership in energy and environmental design
MPC	Model predictive control
SDT	Sustainable digital twin
VAV	Variable Air Volume
EOC	Energy operation center
IFC	Industry foundation classes
AM	Asset management
SC	Smart campus
WSN	Wireless sensor network
MEP	Mechanical, electrical and plumbing
ZED	Zero energy districts
RES	Renewable energy system
GIS	Geographical information system
FMM	Facility management and maintenance
ANN	Artificial neural networks
SVM	Support vector machines
AHU	Air handling unit
BMS	Building management system

Acknowledgements
Not applicable.

Author contributions
ASCC contributed with the research methodology, analysis of previous studies and proposed DT framework, discussion and conclusions. MJ contributed with the general layout of the document, analysis of commercial tools, discussion and conclusions.

Funding
Open access funding provided by University of Southern Denmark This research was carried out under the '***DanRETwin: A Digital Twin solution for optimal energy retrofit decision-making and decarbonization of the Danish building stock***' project, funded by the Danish Energy Agency (Energistyrelsen) under the Energy Technology Development and Demonstration Program (EUDP), ID number: 640222-496754.

Availability of data and materials
All data generated or analysed during this study are included in this published article and its supplementary references list.

Declarations

Ethics approval and consent to participate
Not applicable.

Competing interests

The authors declare that they have no competing interests.

Received: 28 December 2023 Accepted: 12 February 2024
Published online: 26 February 2024

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