Characterizing BIM-enabled Digital Twins for Building Facilities Management

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Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

Master of Science
In
Civil Engineering

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September 19, 2022
Blacksburg, Virginia

Keywords: Digital Twins, Building Information Modeling, Facilities Management,
Operations and Maintenance, Energy Management

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ABSTRACT

Digital twins (DT) describe the integration of the physical and digital worlds with the aim of optimizing real-world operations and functions. The digital twin concept has gained increasing attention across industries in the past decade including the building sector. However digital twins remain ambiguous with various existing definitions and characteristics. While DTs include all life cycle phases, ultimately their goal is the optimization of operations during the use phase. Of the building life cycle phases, building facilities management (FM) is responsible for considerable costs and energy consumption and has potential for improvement through DT implementation. Along with increased building information modeling (BIM) implementation, recent advances in data driven technologies have encouraged the exploration of DT in the building sector. BIM has been coupled with technologies such as internet of things (IoT), data analytics, and cloud computing to optimize various FM functions often resembling DT. This study has reviewed existing literature on digital twins in facilities management using a structured literature review and characterized similar characteristics and definitions by different authors. Additionally, DT implementation in different FM application areas was quantified and analyzed. Results show that DT implementation in FM is still at nascent stages with major challenges surrounding standardization and data integration.

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GENERAL AUDIENCE ABSTRACT

Digital twins (DT) describe the integration of the physical and digital worlds with the aim of optimizing real-world operations and functions. The digital twin concept has gained increasing attention across industries in the past decade including the building sector. However digital twins remain ambiguous with various existing definitions and characteristics. DTs include all building life cycle phases from design, and construction, to operation and maintenance. Ultimately their goal is the optimization of operations also referred to as facilities management during the use phase. Of the building life cycle phases, building facilities management (FM) is responsible for considerable costs and energy consumption and the has potential for improvement through DT implementation. Building information modeling (BIM) describes geometric and semantic information of physical assets and has been used to optimize operations in FM. Along with increased BIM implementation, recent advances in data-driven technologies have encouraged the exploration of DT in the building sector. BIM has been coupled with technologies such as the internet of things (IoT), data analytics, and cloud computing to optimize various FM functions often resembling DT.

This study has reviewed existing literature on digital twins in facilities management using a structured literature review and characterized similar characteristics and definitions by different authors. Additionally, DT implementation in different FM application areas was quantified and analyzed. Results show that DT implementation in FM is still in nascent stages with major challenges surrounding standardization and data integration.

ACKNOWLEDGEMENT

I would like to thank my advisor and committee chairman Dr. Farrokh Jazizadeh for his guidance with my thesis and support throughout my master's studies. I would also like to thank my committee members, Dr. Josh Iorio and Dr. Rodrigo Sarlo for their valuable insight and encouragement.

I am extremely grateful to my family for their unconditional love and support. Without my parents' continuous encouragements and guidance, I would not be where I am today. I cannot thank you enough.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Introduction

The operations and maintenance (O&M) phase, alternatively referred to as facilities management (FM), is a critical stage of the building lifecycle with considerable cost and environmental impacts. FM accounts for the longest phase within the building lifecycle and is the greatest contributor to overall building cost and energy. Therefore, research efforts have focused on leveraging technological advancements to enhance efficiency in FM operations. Building Information Modeling (BIM) is one of the pivotal components in these efforts due to its ability to efficiently manage and share various data resources. BIM has been defined as a digital representation of all relevant geometric and semantic information of a physical asset [1] and can act as a data repository throughout the building lifecycle. In the past decade, studies have identified technological and human related factors through which BIM could support FM activities. During early BIM development, Becerik-Gerber et al. reviewed its potential for implementation in FM and provided ten comprehensive application areas [2]. Several applications described the integration of BIM with additional FM systems and technologies.

Along with widespread BIM implementation, advances in digital technologies, such as the internet of things (IoT), artificial intelligence (AI), and cloud computing have shifted attention to a new concept defined as digital twins (DT). DTs have been described beyond a virtual representation of the physical space. Moreover, DT emphasizes the connection between the virtual and physical worlds and analyzes their interaction for the purpose of optimizing asset or building performance. The use of BIM with recent digital technologies during FM has been the topic of evolving studies and often described as a Digital Twin. These studies demonstrate potential in enhancing FM activities through capabilities such as inspection, monitoring, data analysis and visualization, and automatic control also referred to as digital twin services [3]. For example, Lagüela et al. integrated BIM with 3D point cloud data and thermographic imaging to automatically capture and visualize geometric and thermal data. This automated process for updating BIM models in FM helped support building inspection and defect detection [4]. In a similar study, Valinejadshoubi et al. monitored and analyzed thermal comfort by integrating BIM with IoT [5]. Finally, Yenumula et al. integrated BIM with heat sensors in a building and achieved automated control of a signage system to support emergency management in FM. The heat sensors detected fire which then triggered a route simulation through BIM, leading to sign activation of the best possible route [6].

This integration of BIM's data management and collaboration capabilities with IoT, laser scanning, and other information communication technologies has resulted in models and applications that align with the Digital Twin concept. To help differentiate these applications from DT, several authors have adopted the three levels of integration introduced by Kritzinger et al. in manufacturing [7]. The three levels help define the evolution towards DT based on their data exchange capabilities between the digital and physical space. Fuller et al. adopted these levels of integration classifying literature that described the use of BIM with technologies such as Internet of Things (IoT) and Artificial Intelligence (AI) amongst others [8]. IoT sensors and actuators are key technologies that enable the integration of the digital and physical spaces to help establish DTs. Sensors can be used to collect real-time data from the physical space while actuators enable control of the physical space. DTs have also been defined through a five-dimension model or creation framework that describes data to be at the center of DT. Another important aspect described is the services performed by DT such as monitoring, analysis, and control that can enhance FM applications [9]. For building FM, BIM alone is not a comprehensive solution and lacks the digital structure of FM information and processes. However, it provides important data management capabilities and includes a great amount of building information required [10].

Several studies in the literature have reviewed the potential for BIM implementation throughout the building lifecycle and compared BIM applications to DT. For example, Deng et al. developed a 5-level taxonomy from BIM to DT based on BIM's integration with other technologies and increased capabilities [11]. However, this review focuses on the evolution from BIM to DT and lacks a review of existing studies claiming DT applications in FM. In a similar study, Lu et al. reviewed existing literature on BIM in O&M and proposed a BIM-enabled DT framework to enhance O&M. Similarly, their study shows how existing BIM applications and their integration with other technologies resemble or qualify as DT [12]. Meanwhile other studies have focused on generalized applications for industries such as construction or the civil sector which include various types of infrastructure. This study aims to fill this gap and provide a comprehensive understanding of DT characterization, capabilities, and applications in the context of building FM with a focus on BIM's contribution to the development of DT. Based on this objective, this research seeks to answer the following questions:

1) What are existing Digital Twin concepts and how have they been perceived across different studies from manufacturing to building FM applications?
2) What are the benefits of DT applications in FM? How do DT technologies enhance FM applications?
3) What are the challenges associated with DT applications in FM?

To address these questions, interviews and surveys could be challenging given that the literature suggests limited implementation on the topic. Therefore, rather than reaching out to industry professionals, existing literature was reviewed to gather authors' perspectives on DT. Moreover, DT implementation in specific FM applications is evaluated and quantified to determine its potential.

The remainder of this paper is structured as follows. Section 2 details the structured literature review methodology including a background subsection discussing the contributions of review papers compiled and the literature compilation process used. Section 3 introduces four categories of DT characterizations along with examples of how different authors have perceived the notion of DT. In the next Section 4, we discuss DT applications and technologies with a focus on BIM's contribution. Section 5 discusses the challenges and gaps associated with DT and compares them to previously established challenges for BIM implementation in FM. Finally, Section 6 summarizes the key findings of this study and future directions for DT development.

Structured Literature Review Methodology

Background

This study uses a structured literature review methodology to compile a comprehensive list of existing research on digital twins in building FM. Table 1 describes DT review papers from the compiled literature which present a wide scope of infrastructure projects throughout their lifecycle. Despite challenges and changes required for DT implementation, its leading potential for automation and optimized operations in buildings has increased global demand within the past decade. Amongst other benefits, Rafsanjani et al. projected DT potential for cost savings in O&M to be $400 million in the AEC industry excluding residential buildings. However, difficulties such as interoperability, real-time data access, and lack of utilization have hindered DT development in AEC related fields. For example, Fuller et al. reviewed existing literature on AI, IoT, and DT applications in manufacturing, healthcare, and smart cities. They found that healthcare and smart cities (including buildings) were still behind on DT development when compared to manufacturing. Furthermore, they highlight the lack of a clear definition for DTs stating that there was "no real difference in definition since being initially coined in 2012" [8]. Similarly, Jones et al. reviewed existing literature on DTs across all industries and proposed an operating framework with 13 key characteristics of DT as shown in Figure 1. The virtual to physical connections and vice versa were defined through the terms Metrology and Realization. Metrology describes the measurement of the state of entities or processes within DT. Meanwhile Realization involves changing the state of entities or processes. Moreover, Jones et al. state that DT research efforts lack development within related fields such as BIM and DT integration.

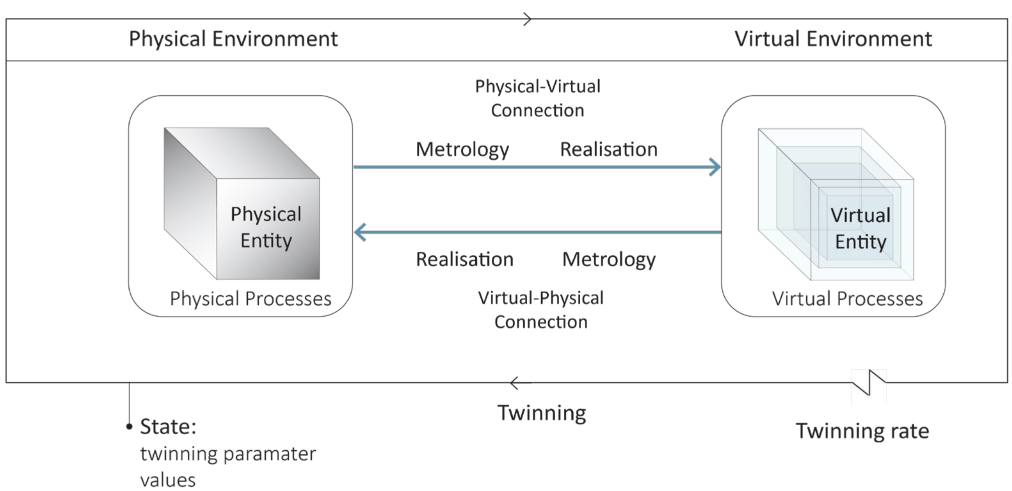

Figure 1: 13 Key DT Characteristics demonstrated in the Twinning Process by Jones et al. [13]

Several studies focused on DT applications in the architecture, engineering, construction, and operation (AECO) industry. Opoku et al. systematically reviewed DT in the construction industry throughout its lifecycle and synthesized that the term DT was often used to describe BIM applications. Moreover, they found different existing definitions for DT with no common concept. In a different study, Jiang et al. also reviewed DT throughout its lifecycle and proposed changes specific to the civil sector. Given that the DT concept emerged from manufacturing and automotive industries, they include seminal studies in which many papers from the compiled literature have borrowed DT definitions and characteristics. Among the review papers listed in table 1, we excluded these seminal papers which are discussed in detail in Section 2. Overall, research efforts centered on digital twins in the AECO industry cover a wide scope of infrastructure types and include all lifecycle phases. However, they lack a detailed review on DT in building FM.

Table 1 Digital Twin review papers in the compiled literature.

Reference	Contribution
[14]	Reviewed the use of BIM, Extended Reality, and Digital Twins for O&M in **smart buildings**. They focused on BIM-based DT with XR devices and conceptually demonstrated user interactions.
[15]	Reviews digitization of **AECO industry** and integration of construction 4.0 tools to achieve life-cycle DT.
[16]	Digitization of FM, review on technologies such as XR, IoT and ML focusing on integration with FM-enabled BIM. State DT is the goal/future of revolutionizing FM.
[11]	Characterized the evolution from BIM to DT using five levels describing the integration of BIM and industry 4.0 technologies.
[8]	Reviewed AI, IoT, and DT technologies & applications in **manufacturing**, **healthcare**, and **smart cities** with focus on analytics. They discussed DT concepts and categorized their development/ evolution.
[13]	Systematically reviewed DT papers in the past 10 years **across industries** and proposed 13 key characteristics of DT throughout its lifecycle. They developed a DT framework that outlines its operation.
[3]	Reviewed and compared DT, BIM, and Cyber-Physical Systems (CPS) in the **civil sector** throughout its lifecycle. They identified key characteristics and recurring themes of DT.
[17]	Systematically reviewed DT in the **construction industry** throughout its lifecycle and provided six DT application areas: BIM, structural system integrity, FM, monitoring, logistics processes, and energy simulation. According to their findings, BIM applications continue to develop but have not reached DT level.
[17]	Reviewed the evolution of DT throughout its lifecycle in **AECO-FM** through scientometric analysis. They covered a wide range of related topics emphasizing building lifecycle management, information integrated production, virtual-physical building integration.
[18]	Reviewed technologies used in FM by the **AECO industry**. They focused on trends in FM, information management, emergency management, and energy management.

[19]	Provided trends and cost savings related to DT and VDC and the integration of technologies such as AI and AR in the **AEC industry**. They projected $950 million saving in design and construction and $400 million in O&M for non-residential projects.

Literature Compilation Process:

The literature compilation process focused on digital twins within buildings FM. The terms “Operation and Maintenance” and “Energy Management” encompass most FM services and were therefore included in the literature search. Figure 2 outlines the databases, search terms, results retrieved, and results included from the search process. The databases ScienceDirect, Google Scholar, and Engineering Village were used to search the following combinations of keywords:

- “Digital Twin” and “Operation and Maintenance” and “Building”
- “Digital Twin” and “Facility Management” and “Building”
- “Digital Twin” and “Energy Management” and “Building”

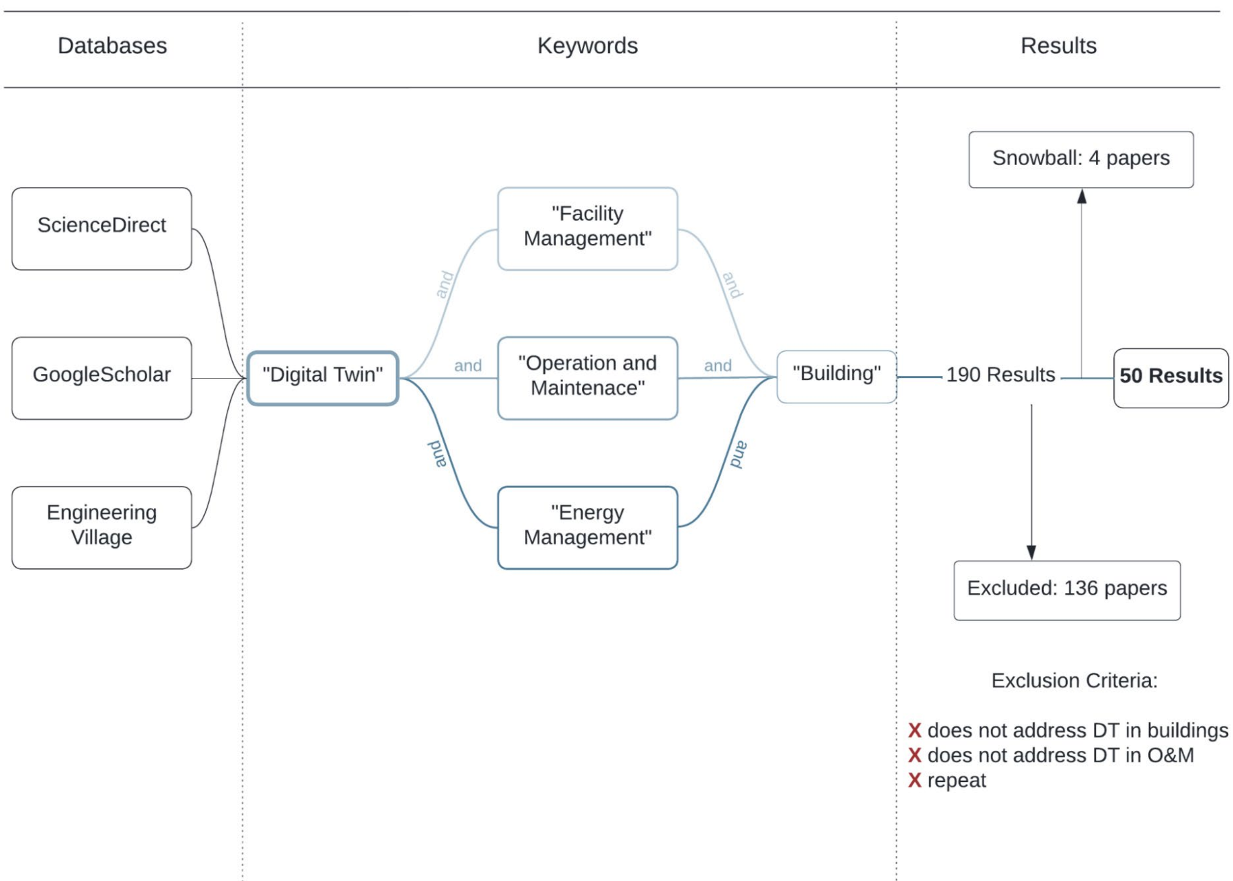

Figure 2 Literature Compilation Process

To ensure the studies compiled contributed to our research, a few screening criteria were used. Studies that failed to address at least one aspect of digital twins in buildings were removed. Studies that did not describe DT in the context of FM were also excluded. Since search terms were similar and used on multiple databases, repeated results had to be filtered out. After screening was completed, compiled literature from the search was reduced from 190 to 46 results. Additionally, four referenced seminal papers about the inception of digital twins in manufacturing were included through literature linking. Finally, 50 results from the literature compilation process were included.

Initially another similar search was performed with the keyword “BIM” in the place of “digital twin” to better understand BIM’s contribution to the development of DT. Results were narrowed down from 184 to 120 using the same criteria except the keyword “digital twin” was replaced with “BIM”. Several studies included both keywords “BIM” and “digital twin” and were found in the results for both searches. Collectively these repeated studies provided an extensive review of BIM in building FM. Additionally, most of the DT studies from the initially compiled papers included some aspect of BIM in the context of digital twins. To better depict the contribution of BIM to digital twins, results from this secondary “BIM” search that did not include DT aspects were removed.

The final compiled literature is thoroughly analyzed to identify and map patterns of digital twin concepts, applications, frameworks, and solutions in building FM. Various data visualizations methods such as graphs and flowcharts are used to address the objectives of this research.

Methodology

A qualitative review of the compiled literature was used to identify existing DT definitions and concepts in building FM. Many of these definitions/concepts were adopted from seminal DT studies in manufacturing. Therefore, we included these seminal studies in our compiled literature and evaluated their development from manufacturing and other industries to building FM. Several other studies were funded by the Centre of Digital Built Britain and shared their own DT concept. We categorized these existing DT concepts into four different DT characterizations and compared the original DT concept to how it has been perceived in building FM. Similarly, we identified existing DT applications and how they enhanced FM activities. The technologies used were also evaluated with a focus on BIM and mapped to their contribution to different application areas. To conclude we identified and evaluated the challenges and gaps associated with DT applications. Figure 3 illustrates proposed methods of fulfilling this study's objectives.

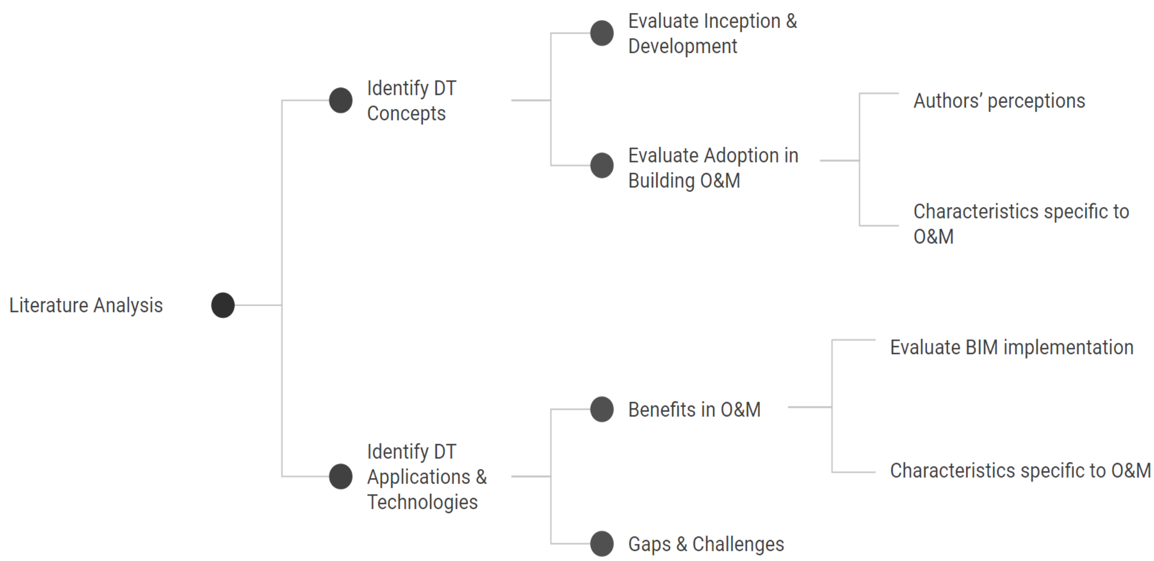

Figure 3 Literature Analysis Methodology

From the compiled literature on DT in FM and as shown in Figure 4, 45% of studies were original implementation research. 16% were original conceptual research with no real-world implementation. Finally, 39% were review papers including seminal papers added through literature linking described above. Figure 5 shows the increase of DT studies in recent years from the compiled literature. Similarly, the graph includes the seminal papers which represent papers from 2012-2018 with the earliest papers on DT in building FM starting at 2018.

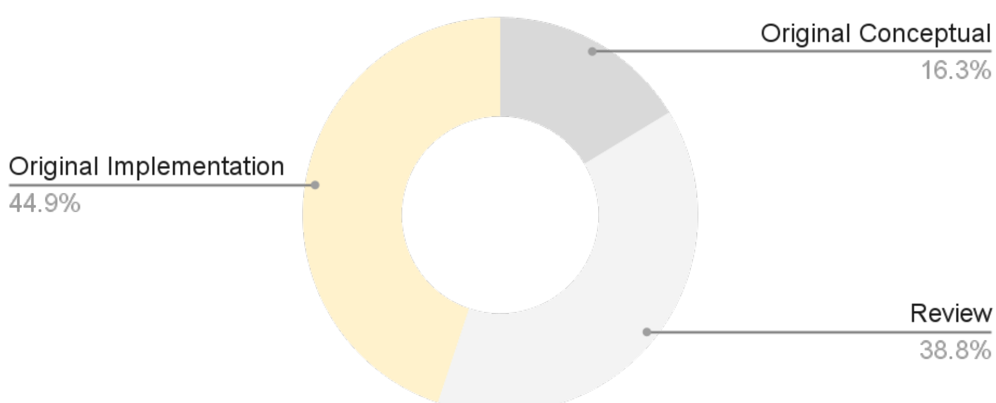

Figure 4 Compiled Literature Type Distribution

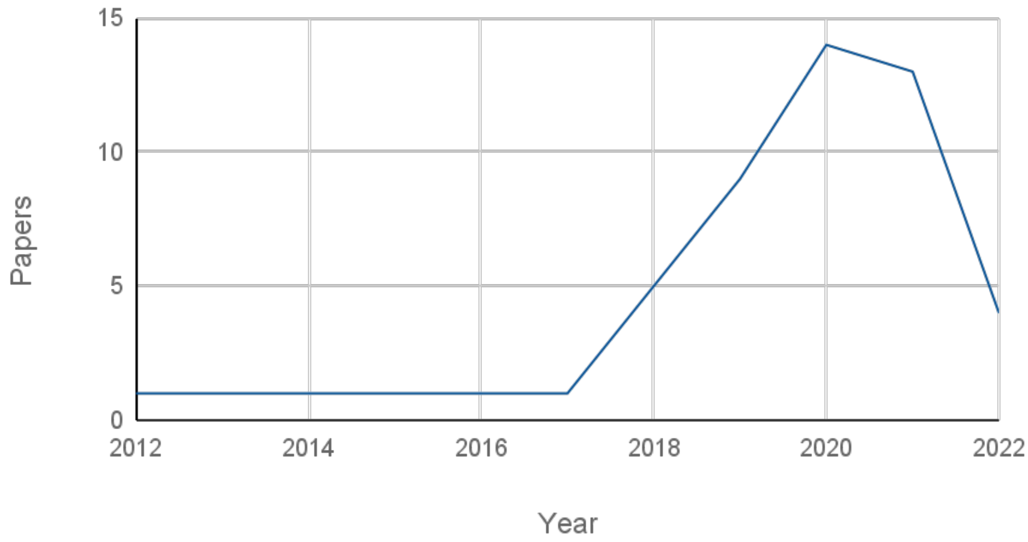

Figure 5 Compiled Literature Timeline

Beside DT characterization categories based on seminal papers, an additional category was identified from several studies funded by the Centre of Digital Built Britain (CDBB). Their efforts to create a national digital twin has also had widespread influence over research in the United Kingdom. Figure 6 shows much of the compiled literature is written by authors from the UK followed by the US. However, more than half of studies attributed to the US are the seminal studies from 2012-2018. Overall, in a global context the topic of DT in building FM seems to have gained the most interest by European countries.

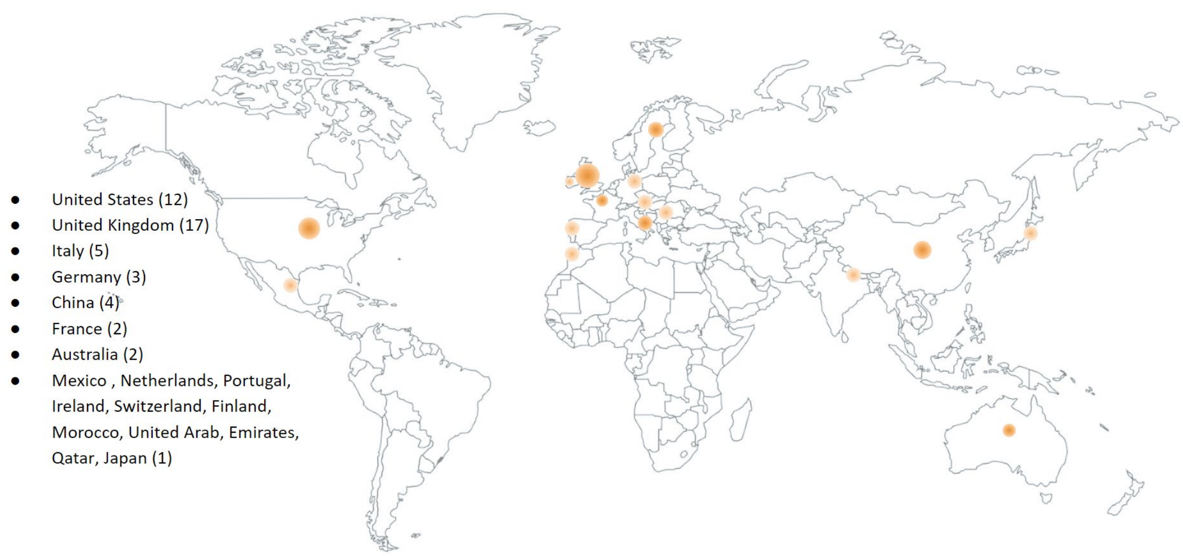

Figure 6 Geographic Distribution of Authors from Compiled Literature

Digital Twin Characterization and Adoption

Since DT's first introduction in manufacturing and aerospace, advances in digital and data-driven technologies within the past decade have facilitated its adoption across multiple industries. DT adoption by different industries presented varying interpretations and characteristics of the process [14]. In this section, we have sought to understand how different studies in the building FM applications have related their work to the DT concept and how these efforts are characterized with respect to the definitions and characterizations of four seminal studies [7], [9], [20], [21]. Therefore, in what follows, we have presented a synthesis of major characterizations of each well-known study, followed by an assessment of their adoption for building FM applications from the compiled papers. In the end, we have classified and summarized the compiled literature on building FM by their characterization and attribution to the seminal studies.

1. DT Origins - Grieves' Characterization

In this section we describe the characteristics of the digital twin concept in its early development and discuss their adoption by studies in building FM. The Digital Twin concept emerged from the field of manufacturing twenty years ago in a lecture by Grieves and Vickers on Product Lifecycle Management [20]. The concept was based on their work with NASA who defined DT as "an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin" [22]. NASA's Apollo program created the first digital twin where a real-life replica of the space shuttle sent to space was built. The replica remained on Earth mirroring conditions in space and running simulations for problems encountered in space to recommend the best solution. The DT performed high risk applications where accuracy was a critical requirement since mistakes could be catastrophic.

Grieves later described the core concept of digital twins and defined its three main components: (1) Real Space, (2) Virtual Space, and (3) their exchange of data and information [20]. The real space referred to an existing physical system while the virtual space was a constructed digital system that represented the real space "from micro-atomic level to the macro" [20]. Grieves defined that any information obtained from inspecting the real space could be obtained from the virtual space in a digital twin. The real and virtual spaces are linked in both directions throughout the DT lifecycle. Data flows from the real to virtual space and information flows from the virtual to real space creating a live connection called "twinning". Moreover, digital twins store historical data from the twinning process, continuously studying the past and predicting the future to optimize performance [20].

Furthermore, Grieves defines three digital twin types that evolve within a DT environment along the lifecycle phases of DT as shown in Figure 7 [23]. Starting at the create phase, the first DT type is the digital twin prototype (DTP). A DTP contains all the digital information about a physical subsystem in the real space such as its digital geometry and material specifications. Multiple DTPs come together to represent the entire physical system. This is similar to how BIM objects and components can collectively represent a building model. The DTPs exist in a digital twin environment (DTE) or application layer with predictive capabilities. Predictive services enable DTPs forecast future states of the physical system using simulation methods such as finite element analysis (FEA). The second DT type developed in the production phase is the digital twin instance (DTI). With the use of sensors, a data flow link is established between physical subsystems and DTPs creating DTIs. At this phase, a DTI performs predictive and interrogative services based on specific real-time and historical data from the physical subsystem. For example, an HVAC pump DTI can be interrogated for its current system state and failures can be predicted based on its run time. The assembly of multiple digital twin instances and an additional link from the virtual to physical space make up a digital twin aggregate (DTA). DTA can run predictive and interrogative services on multiple digital twin instances linking data from various physical subsystems [23].

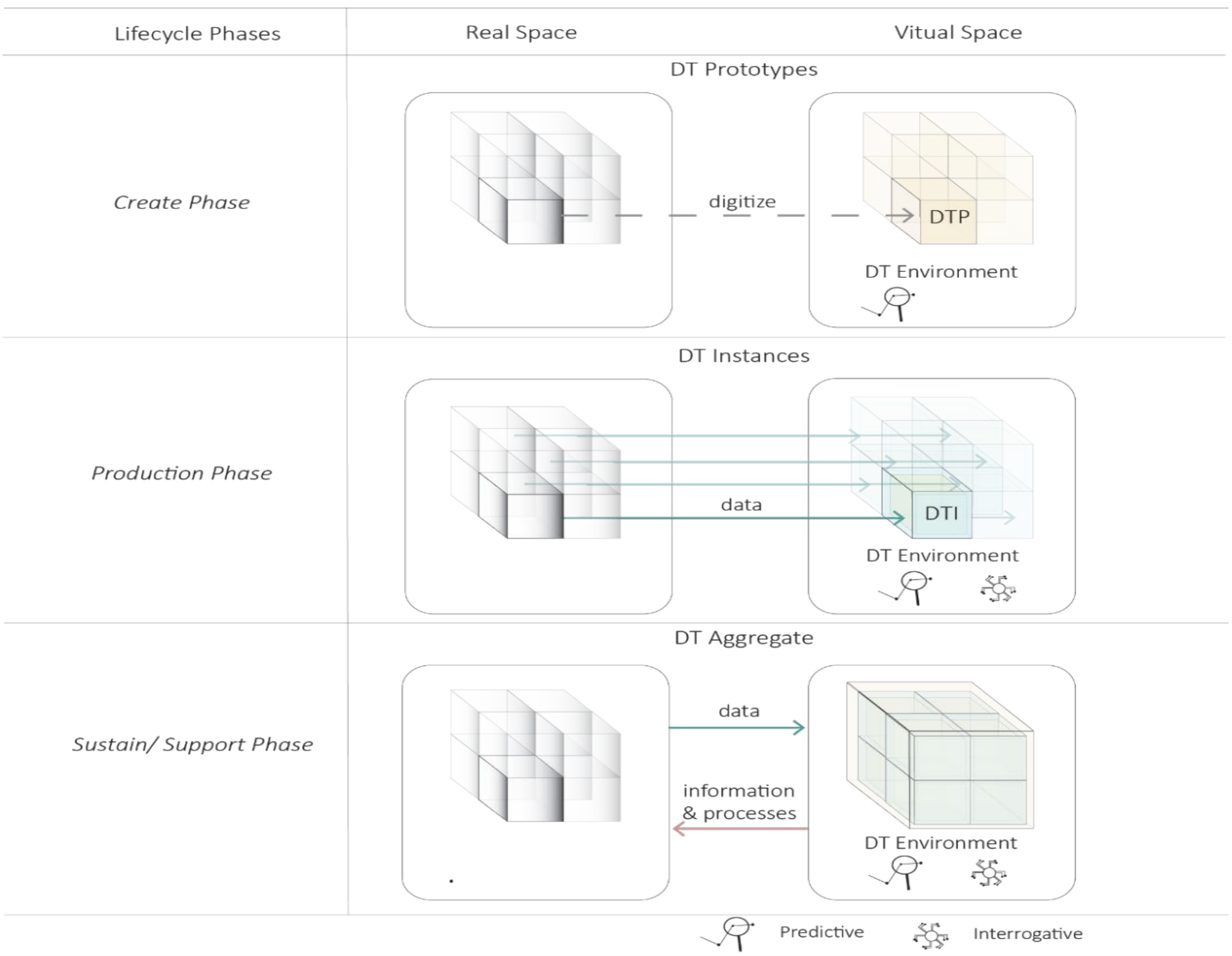

Figure 7 Digital Twin Types in Lifecycle phases by Grieves [23]

To illustrate Greives's DT types in building FM, Vering et al. developed a digital twin design (DTD) approach for HVAC systems [24]. They demonstrated this approach for a ventilation system digital twin and proposed two additional DT types to the three DT types described above. The digital twin concept (DTC) was added to the plan phase at the beginning of the lifecycle to set objectives and requirements for the implementation of DT. Digital twin knowledge (DTK) was added to the dispose phase at the end of the lifecycle to evaluate stored operational data from all previous DT phases and support the create phase of the next DT. The following lists the constituents of the DT types implemented to achieve the ventilation system digital twin [24]:

- DT Concept: level of accuracy, simulation speeds, ventilation system characteristics & requirements (volume flows, temperatures, pressure levels, and their power consumptions)
- DT Prototypes: parametric simulation models of heat exchanger, ventilator, air filter, heater, cooler, sinks, and target room.
- DT Instances: manually calibrated simulation models that each receive data from IoT sensors through an established communication protocol. Simulations are run through a user interface.
- DT Aggregate: Simultaneous data simulations from multiple digital twin instances to predict failures and optimize operation. Recommendations are automatically sent to the ventilation system (theoretically discussed by Vering et al. as opposed to implementation).
- DT Knowledge: evaluation of stored operational data from entire use phase and DT architecture (theoretically discussed by Vering et al. as opposed to implementation)

Vering et al described ventilation systems as complex systems with unpredictable behavior well suited for DT [24]. With real-time data, DT instances of air filters predicted replacements and reduced operational costs of the ventilation system. However, operational efficiency objectives were set through variable values selected in the DT Concept and required predictions at the DT Aggregate level. An interface that could simultaneously run simulations from multiple DTI and manipulate parameters was still being developed. As a result, DT aggregate and the following DT knowledge were theoretically implemented. Apart from these challenges, stochastic behavior, and similarity of HVAC systems in different buildings make these complex systems well suited for DT.

Stojanovic et al. adopted Grieves definition of DT and developed a framework for generating digital twins based on 3D point clouds [25]. They describe DT as a “digital duplicate of the built environment” with the ability to assess past and current states to predict future states. They used a segmentation algorithm to extract semantic data from 3D point clouds and associated it with a BIM model to visualize as-is conditions of an interior space for FM. The updated as-is BIM model, similar to Grieves’ description of DTP, is regarded as basis data for DT. Unlike replicated manufactured products, building interiors have unique spatial arrangements that make it difficult to automatically capture, model and update without manual input. Additionally, components such as walls and doors, or even furniture do not require real-time updates for FM. Stojanovic et al. have focused their future efforts on developing a web-application that combines 3D point clouds and real-time sensor data with an as-is BIM model [25]. Although predictive simulations can be performed at DTP level, a higher level of accuracy can be achieved at DTI level. For example, an as-is BIM model can be used to predict space requirements based on available usage patterns from other spaces however more reliable predictions could be achieved with real-time occupancy data. While this may be beneficial for public service buildings and museums, it would not be suitable for a single-family home and other residential buildings.

Similarly, Angjeliu et al. adopted Grieves' DT characterization and developed a digital twin modeling methodology to help preserve the safety of historic buildings. They combined geometric data from 3D point clouds and sensor data from the structure with BIM to study and predict structural response of the building. Accurate digital representations for DT require extensive data collection throughout their lifecycle. Historic buildings have a long-term life and contain large amounts of data. Thus, Angjeliu et al. specify in their DT development that only part of the building's data was collected at a specific period of time in their history. Furthermore, the virtual space was described as "an idealized version of the collected data" for the purpose of structural health simulation. While Stojanovic et al. described their developed framework as basis data for DT, Angjeliu et al revised Grieves definition to suit their developed DT. Dynamic processes in buildings such as mechanical systems can be well suited for DT services such as monitoring and control. In contrast, changes in the geometric state and material properties of buildings occur over long periods of time, do not require real-time updates, and can be difficult to monitor.

2. DT Evolution - Levels of integration

The contrasting definitions on DT presented in a review of studies / practices in manufacturing inspired another seminal study by Kritzinger et al.: DT's three levels of integration [7]. They provide a simplified method of distinguishing digital twins based on the presence of automatic data exchange between a physical object and a digital object using three levels of integration: (1) Digital Model, (2) Digital Shadow, and (3) Digital Twin.

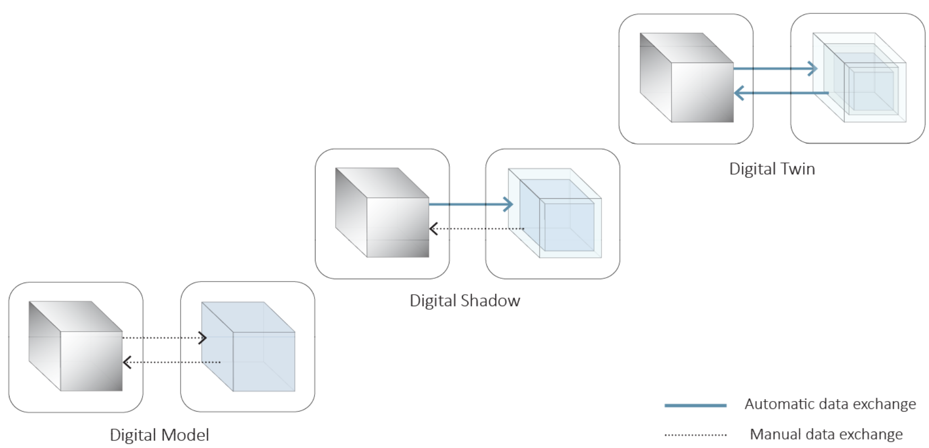

Figure 8 Levels of Integration [7]

As shown in Figure 8, the digital model is the first level of integration. Like the DT prototype (DTP) defined by Grieves, it digitally represents an existing or non-existing physical object through manual data exchange. Digital shadows, also like DT instances (DTI), further integrate the digital object with the physical object through automatic data exchange from physical to digital object. Finally, a digital twin is a fully integrated digital model with automatic exchange present from both directions of the physical and virtual objects. Unlike a DT aggregate with multiple DT instances, Kritzinger et al. defines a digital twin as a physical and digital object with bi-directional automatic data exchange [7]. Kritzinger et al. reviewed DT studies in manufacturing from 2014 to 2018 specifically noting their use of the term 'digital twin'. Using the three levels of integration described, they classified 35% as digital shadows, 28% as digital models, while only 18% fit the digital twin description and the remaining were undefined [7].

The majority of studies classified as digital models and shadows as shown in Figure 9(a). Similar to DT prototypes and DT instances in the create and production phases, they mostly focused on production planning and control. However, since these studies were described as DTs, they suggest common misconceptions. Barriers associated with the digital models and shadows included difficulties establishing data connectivity and developing real-time simulations preventing them from developing into digital twins.

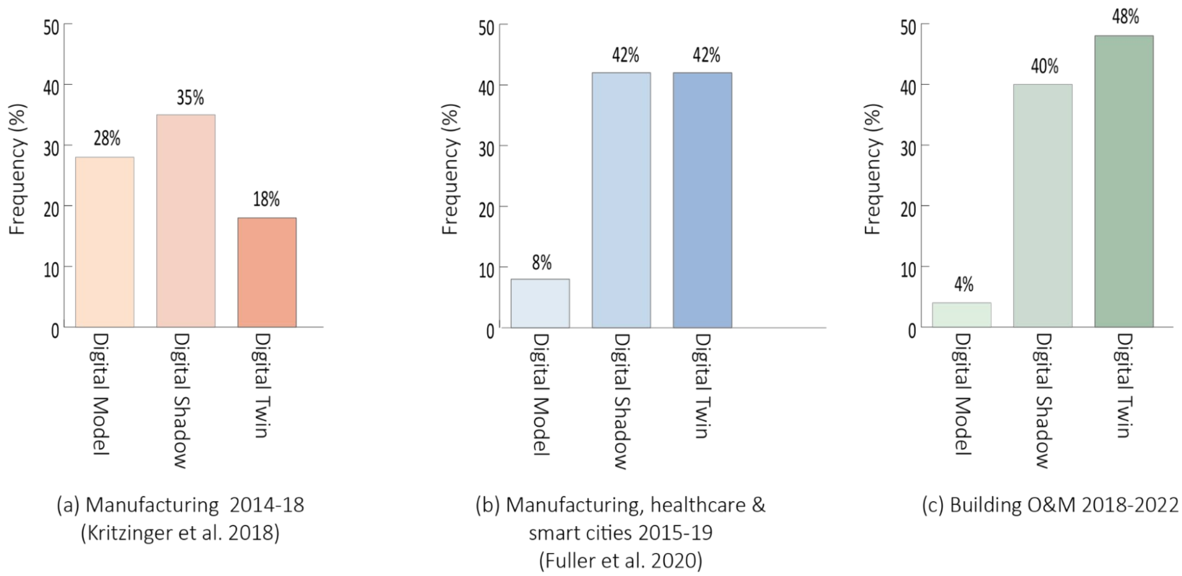

Figure 9 Levels of Integration classifications in literature

Kritzinger's levels of integration were adopted by Fuller et al. to evaluate digital twins across industries [8]. Fuller et al. studied literature on DT in manufacturing, healthcare and smart cities combined from 2015 to 2019 classifying the studies as 8% digital models, 42% digital shadows, 42% digital twins and the remaining undefined as shown in Figure 9 (b) [8]. The adoption of AI, IoT, and other data driven technologies has facilitated the integration of digital twins. However, different adoption rates across industries and a lack of standardization have also hindered DT implementation [8]. For example, DT modeling methods for the human body, traffic systems, or even machinery all require a multidisciplinary approach. As a result, DT implementation encounters difficulties with data fusion due to lack of standardization [8].

Similar to the above-mentioned studies, we have classified the compiled literature on DT in building FM using the three levels of integration excluding review papers [7]. Given the complexity of building systems and different levels of automation present in the compiled literature, the following criteria was used:

- If study includes two or three levels of integration for different physical and digital objects, the highest level of integration is used.
- Digital shadows must include at least one automatic data connection from the physical to digital object.
- Digital twin must describe at least one automatic data connection in both directions from the digital to physical object and vice-versa.

- Digital models are only connected to a physical object through manual exchange of data.

Many different levels of automation were described in the compiled literature as shown in Figure 10. Therefore, studies classified as digital shadows included the following levels of automation:

- Manual exchange from physical to user and automatic exchange from user to digital
- Automatic exchange from physical to user and manual exchange from user to digital
- Automatic exchange from physical to digital

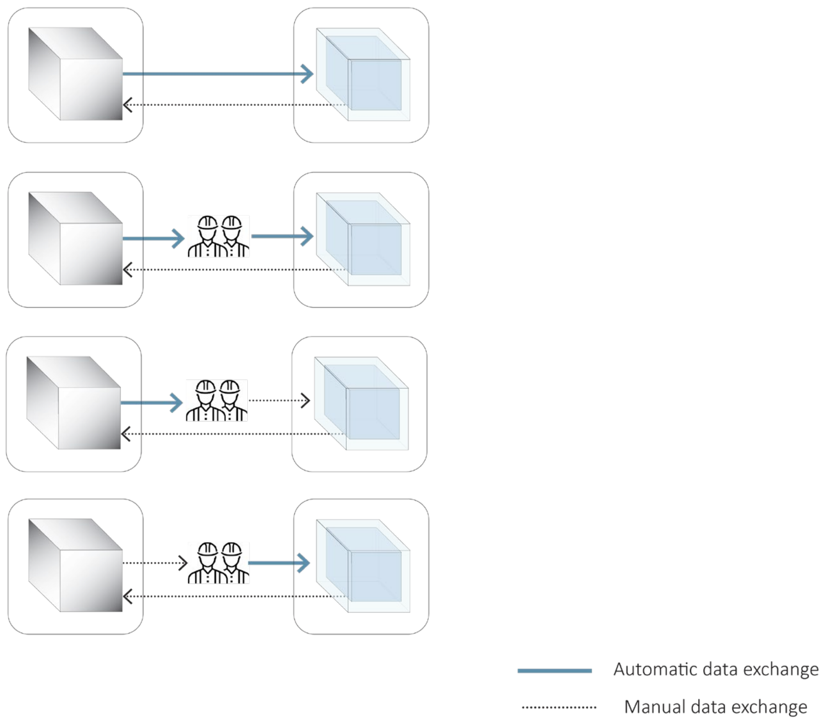

Figure 10 Different Levels of Automation in Digital Shadows

Similarly, studies classified as digital twins included these different levels of automation from user to digital and from digital to user. The literature classification of the compiled literature is shown in Table 2. For example, Lu et al. developed a methodology for routine Facility Management (FM) update of as-is BIM models based on captured images by FM personnel and CAD drawings that was classified as a digital shadow [26]. The images captured by FM personnel are considered manual exchange from physical to user while the updated as-is BIM model represents the automatic exchange from user to digital object. In a digital twin classified study, Antonino et al. used IoT sensors to monitor user movement triggering work orders when maximum occupancy was reached [27]. However, work orders had to be manually resolved placing FM personnel in the middle of the connection from virtual to physical. The compiled literature was categorized as 48% digital twins, 40% digital shadows, 4% digital models and the remaining undefined as shown in Figure 9 (c). In comparison to the previous classification studies [7], [8] results from the compiled literature on building FM suggest a rise in digital twin studies. However, the defined digital twin studies do not meet Grieves requirements for a DT aggregate. Buildings have extensive complex systems which make it challenging to establish bi-directional data flow links between all physical and digital subsystems. Peng et al. came relatively close to developing a DT aggregate for a new hospital building. They established two-way automatic connections for energy management, equipment maintenance, security, healthcare information, and medical gas pipeline systems but faced difficulties with building automation (BA) systems [28]. Although they were able to receive data and monitor the BA systems, detected problems had to be manually assigned to workers. Furthermore, increased automation can cause major risks and safety concerns for the hospital patients and healthcare workers. Therefore, a building's function and specific requirements are essential in determining a digital twin's level of integration and automation.

Table 2 Literature case-studies classified by levels of integration.

Reference	Contribution	Level of Integration
[29]	Developed an energy model to simulate energy consumption and optimize building's design.	Digital Model
[30]	Proposed a semi-automatic modeling methodology using laser scanning coupled with real-time data from sensors for assessing building structural conditions in a historical cathedral.	Digital Shadow
[27]	Integrated real-time occupancy data and building maintenance documents with the BIM model. Achieved automatic work order generation when occupancy capacity is reached.	Digital Twin
[31]	Mathematically modeled and monitored visitor flows in a museum to develop an algorithm that recreates realistic random visitor trajectories as a digital twin. The DT is then used to simulate and optimize the museum entrance system.	Digital Shadow
[32]	Developed a maturity model for assessing digital twins based on dimensions from the Gemini principles. Evaluate using literature and expert surveys. Demonstrate through two use-cases of DT in asset management.	Digital Twin
[33]	Proposed a DT architecture for optimizing energy consumption of multiple buildings and their energy source. Framework integrates BIM, asset and energy data, sensors, simulation models, business value model, and AR/VR.	Digital Twin

[34]	Use a multi-energy optimization DT software by Siemens to forecast and optimize heat and electricity demand in a social housing complex.	Digital Twin
[35]	Developed and demonstrated a framework for monitoring and visualizing light, temperature, and humidity from a building facade.	Digital Shadow
[36]	Proposed a roadmap towards BIM-enabled DT creation based on literature review, RIBA Plan of Work, interviews, and surveys. Evaluate if DT can replace current information exchange methods.	Digital Twin
[26]	Developed a semi-automatic methodology for geometric as-is BIM update based on CAD and images.	Digital Shadow
[37]	Contributed an anomaly detection system for asset monitoring based on extended IFC to facilitate data integration. Demonstrate using two HVAC system pumps within existing building DT.	Digital Shadow
[38]	Developed a visualized AR inspection system for temperature abnormalities in O&M. Use the system in CDBB West Cambridge's digital twin system.	Digital Twin
[39]	Reviewed the creation process and implementation of a campus DT. Integrated extensive building systems with sensors and AI to manage and optimize performance.	Digital Shadow
[12]	Proposed BIM-based framework for O&M that integrates smart assets and supports DT services.	Digital Twin
[40]	Reviewed BIM in asset management and proposed a framework for integration of smart assets with the DT concept.	Digital Twin
[41]	Presented a modeling methodology to optimize the thermal system of a multifunctional roof structure. Tested using sensor data from a 1:1 prototype.	Digital Shadow

[42]	Proposed a modeling methodology for model predictive control and optimization of entire HVAC system in an office building.	Digital Twin
[43]	Developed a location-based information management system with visualization and capable of performing analytics.	Digital Shadow
[44]	Proposed a DT architecture for optimizing energy consumption of multiple assets in a building complex that share an energy source.	Digital Twin
[28]	Detailed the creation and implementation process of a hospital building digital twin from design to O&M phase.	Digital Twin
[25]	Created a web-based application for as-is BIM generation 3D point clouds to support FM.	Digital Shadow
[45]	Developed a surrogate model of an integrated solar chimney with a building based on ANN. Simulated optimized performance in several countries.	Digital Model
[24]	Expanded on Grieves' DT types to create a ventilation system digital twin detailing the processes involved in each life-cycle phase.	Digital Shadow
[46]	Developed and demonstrated a building DT that integrates BMS, sensor, and asset inventory data with AR and asset anomaly detection.	Digital Shadow
[47]	Proposed a framework for updating asset inventories and monitoring indoor environments using an automated mobile scanner and IoT sensors.	Digital Shadow
[48]	Developed a methodology for updating building assets in a BIM model by using localization and semantic mapping of captured images.	Digital Shadow
[49]	Proposed and tested a DT of building assets and indoor environment including AR visualization. Linked detected temperature anomalies to failed assets.	Digital Shadow

[50]	Proposed an asset anomaly detection system and showcased for centrifugal pumps as part of existing building DT.	Digital Shadow
[51]	Proposed an FM framework that facilitates data integration and interoperability and supports decision-making in FM based on four chosen case-studies.	Digital Twin
[52]	Theoretically created a DT framework for FM that uses ML to optimize prediction services. Capabilities include monitoring, predicting, and optimizing performance of building equipment.	Digital Twin

ept:

Tao et al. have authored several studies that have been used to define digital twin characteristics and applications in building FM. In this section, we present their five-dimension model for DT and the services it supports as described in two of their seminal studies [9], [56]. The first paper introduced the five-dimension model and its nine service areas as part of shop floor system (a collection of tools to manage the process of manufacturing) aimed at optimizing the manufacturing process [56]. Meanwhile the second paper was the first to review DT across industries and provided state of the art DT applications in 2019 [9].

The five key DT dimensions as shown in Figure 10, expand on Grieves' three main components, and contain the: (1) Physical entity, (2) Virtual entity, (3) Database (4) Services, and (5) Connections. Like Grieves' description of the virtual space, the virtual entity is described as a "mirror reflection" of the physical entity [9]. The database is at the center of the DT model and enables data-driven services such as monitoring, forecasting, and failure predictions to improve performance of the physical entity. The connections require smart sensor networks to create a data and information flow between all DT parts [9], [56]. In a later review study, Jiang et al. revised Tao's description of connections to better depict DTs in the civil sector. They claimed feedback and control from the virtual to physical entity were not necessary [3],[9] for civil sector applications. Following this notion, multiple studies in the compiled literature on building FM do not describe the virtual to physical connection. We categorized these studies as digital shadows in the above-mentioned levels of integration classification as shown in Table 2. To illustrate the influence of these seminal studies in building FM, we provided examples of studies that adopted these models.

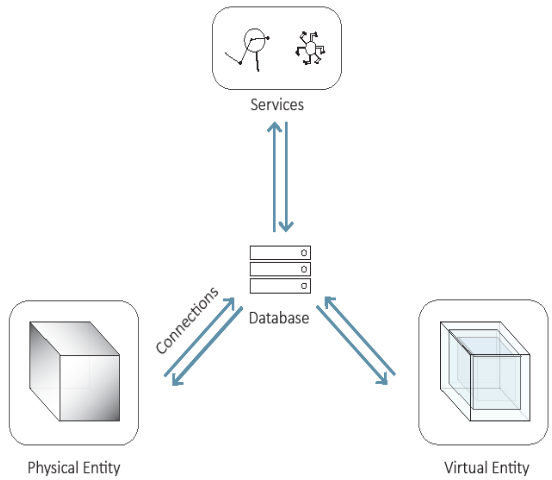

Figure 11 Five-dimension DT model described by Tao et al.

Agouzal et al. adopted Tao et al.'s description of the theoretical foundations for DT [29] for BIM-based energy management. However, they have only relied on some of the dimensions. In doing so, they have developed a BIM model of a three-story building and performed energy simulations based on average measured data of external environmental factors. This representation of DT is missing the live connectivity between physical and virtual entity and falls under the digital model category. On the other hand, in a different study, Khajavi et al. described the physical entity and a wireless sensor network (WSN) as requirements for DT simulation according to Tao et al. [35], [56]. Accordingly, they developed a DT for monitoring environmental data on a building facade using IoT sensors. In this study, the virtual entity was limited to the data from sensors without using high-fidelity 3D BIM models to represent the building. However, applications enabled by the virtual to physical connection such as automatic indoor light adjustment were only theoretically proposed. In a more inclusive conceptual framework, Deng et al. proposed a DT architecture for optimizing the performance of indoor building environments and described five dimensions as (1) Physical building, (2) the BIM model, (3) cloud data storage, (4) energy and comfort predictions, and (5) real-time data collection and control of lighting, humidity, and temperature [11]. Consistent with the interpretation of DT connections for civil sector applications [3], they defined automatic control, enabled by the virtual to physical connection, as a next-generation digital twin feature and not a required one. While automatic control may be well suited in a manufacturing context, FM personnel have an essential role in buildings as they carry out repairs, building control functions, and ensure safety. Moreover, the benefits of automatic control in buildings as they relate to FM functions has yet to be established.

Several studies in the literature are from the Centre for Digital Built Britain's (CDBB) efforts to create a national digital twin (NDT). The Gemini Principles were published by CDBB to establish a common set of principles and definitions towards digital twin development . A digital twin is defined as having a bi-directional connection between a physical and digital asset with “live data flows from sensors” and “real-time control”[21]. CDBB recognizes the variety of purposes for which DTs are created. Therefore, DTs are defined as having appropriate details and scales with regard to their purpose. The NDT aims to facilitate data sharing among digital twins across sectors by establishing an information management framework based on nine principles that stem from three main values of Purpose, Trust, and Function. Most of the studies that have adopted this model were supported by CDBB as described below.

Kirwan et al. focused on Gemini Principle number 5 Openness and evaluated the effects of BIM and data standardization in the construction industry. They considered BIM as critical for DT implementation and analyzed its data exchange requirements. Results from a questionnaire survey found that although many professionals were aware of standardization methods such as COBie, implementation was drastically low. COBie is a static data exchange format that contains information for FM however it does not support real-time data. Kirwan et al. suggested future research should focus on the potential of COBie and determine if it should be removed for BIM Levels 2 and 3. BIM Level 2 is a requirement for all public sector government projects in the UK and describes the use of a common/ exchangeable file format enabling collaboration amongst users. Meanwhile BIM Level 3 is still under development and aims to establish a consistent and collaborative framework outlining data requirements and workflows.

Guided by the Gemini Principles, Lu et al. developed system architecture for DT implementation that was demonstrated in West Cambridge Campus [39. Similar to the systematic division of Grieves’ DT types, Lu et al. established a hierarchy of DT systems and subsystems. A DT at city level integrates DTs from the Building/Infrastructure level such as DTs for buildings, bridges, or pipelines. DTs at infrastructure level integrate sub-DTs from system level such as DTs for HVAC or pumps. This “ecosystem of sub-DTs” is according to the Gemini principles and facilitates the creation of multi-disciplinary DTs such as buildings.

Several studies supported by CBDD, further developed different aspects of West Cambridge campus’s digital twin. Xiang et al. implemented a system architecture by Lu et al. and developed an AR-enabled inspection system to support sub-DTs of building assets [49]. The inspection system was developed to monitor temperature anomalies and automatically highlight the corresponding failed assets. However due to lack of expert knowledge and asset failure scenarios the matching of failed assets could not be realized [49]. In a follow-up study, Lu et al. developed and tested a data integration methodology based on extended industry foundation classes (IFC) to support monitoring and anomaly detection of two centrifugal pumps at the IfM building DT. The pumps were defined as critical assets and therefore monitored through sensor systems. However, their pipes and valves are described as non-critical and are therefore indirectly monitored through temperature anomalies. Lu et al. explained that it is impossible to collect detailed data from all building assets, instead assets are given appropriate detail based on their purpose as described in the Gemini Principles [37].

The Gemini Principles provide a strong set of principles that align efforts in digital twin development for the UK's building industry. Studies shared one DT definition and clearly defined how their work contributed to DT development. The majority of case-studies who adopted characteristics from the Gemini Principles were classified as digital twins according to the levels of integration (Digital model, shadow, and twin). This indicates that a comprehensive DT framework for asset management is key to DT development and emphasizes the importance of standardization agencies in unifying the definitions and implementations.

Non-conforming Studies

There are a number of studies that have focused on DT for Building FM, but they are not fitting to any of the abovementioned DT characterization frameworks. In this section, we have described these studies and their characterization of DT. Several studies have described digital twins as surrogate models or optimization algorithms based on real-time data [45], [31]. For example, Centorrino et al. described a museum digital twin as an algorithm capable of recreating realistic visitor trajectories based on real-time occupancy data [31]. They monitored visitors flow in Galleria Borghese Museum in Rome and developed a DT to optimize their experience. Objectives included controlling the number of visitors in certain rooms for safety reasons and keeping a constant number of visitors to regulate temperature and humidity levels. Similarly, Matsuda et al. monitored real-time data from an HVAC system to develop a prediction model to optimize operations. However, this study does not use the term DT within the article other than being listed as a keyword [42]. In a different study, Wei et al. referred to BIM objects as digital twins. They developed a methodology for extracting semantic data from facility images and mapping it to its corresponding BIM object. This is described as associating captured images with their “digital twin in an information repository” [48]. In summary, these studies have characterized DT as one of the following representations:

- Realistic reconstruction of occupants’ trajectory in a building based on real-time occupancy [31]
- Surrogate model based on ANN [45]
- As-is BIM object [48]
- Predictive model of buildings for optimization by using sensor data from the buildings

Summary of Findings

We have categorized studies in building FM as review, concept, or original implementation research and mapped them to the four seminal digital twin characterizations as shown in Figure 12. The first category of DT characterization is DT origins which describes DT’s inception in aerospace and manufacturing. Particularly, Grieves described DT representations as extensively detailed from “macro to micro”. Accordingly, NASA built a digital twin that was a physical and virtual replica of a space shuttle that mirrored conditions in space. Although forty-eight percent of studies from the compiled literature have been attributed to DT origins, this characterization was found to be challenging to comprehensively implement in buildings. Several challenges exemplified include:

- Difficulty calibrating real-time data from sensors
- Lack of commercially available integrated web-services for achieving DT aggregate
- Automation in creating digital assets

- Complex multidisciplinary building systems
- Different building types and functions with varying requirements (i.e museum, office, etc.)

These difficulties have encouraged more liberal interpretations of DT for buildings. This can be seen in Figure 12 where most studies attributed to DT origins are categorized as review and only 35% are original implementation research. As a result, DT predictive and interrogative services do not achieve the level of accuracy intended by Grieves.

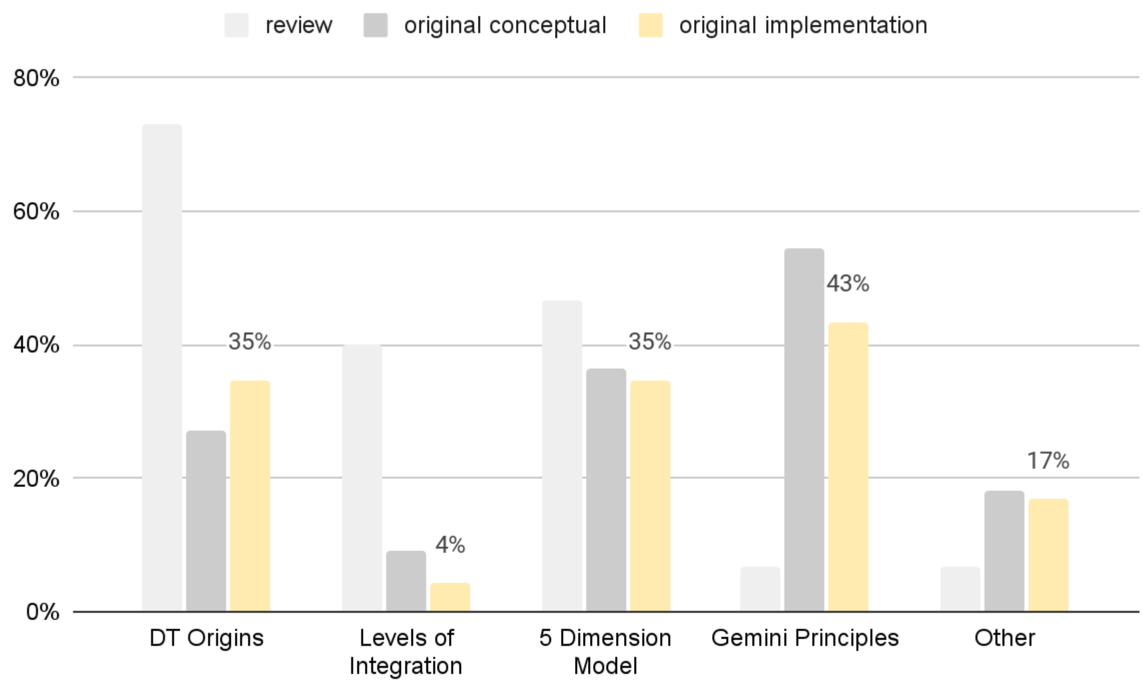

Figure 12 Literature attributed to seminal studies

In the next seminal study Kritzinger et al.'s three levels of integration provide a strategy for differentiating DT based on automatic data exchange. Accordingly, most of the attributed studies from the literature come from review papers. For example, Fuller et al. adopted the three levels of integration to evaluate DT studies across industries. Similarly, this strategy was used to classify DT literature in building FM and found 48% digital twins and 40% digital shadows. However, most studies focused on less than three applications in FM and lacked a comprehensive framework for DT applications. This is further discussed in the next section on DT applications and technologies.

We then described Tao et al. 's 5-dimension model which expanded on Grieves' DT concept and introduced the database and services as two essential DT parts. Data was at the center of DT and the purpose of DT was optimizing performance through DT services. Similar to Grieves, the virtual entity was described as a highly accurate representation of the physical entity. However, by introducing DT services and providing examples of applications in industry, they provide insight into DT creation and implementation. Hence attributed DT characteristics are distributed amongst review, concept, and original implementation research studies.

Finally, several studies funded by CDBB share a common DT definition and values set forth by the Gemini Principles. This provided a unifying set of principles that encouraged studies to build on each other's work for DT development in the UK's building industry. Moreover, a majority of studies classified as DT according to the three levels of integration [7] have characteristics attributed to the Gemini Principles.

Digital Twin Applications & Technologies

This section analyzes and discusses how DT implementation in buildings can enhance FM applications through enabling technologies. BIM has been described as having an essential role in DT development [14] with a majority of DT studies classified as BIM-enabled DT. Subsequently, we adopted ten comprehensive FM application areas from a highly regarded study that categorized FM activities and identified their inefficiencies based on persona interviews. More importantly, they described the potential for increased efficiency through BIM implementation based on survey responses from BIM and non-BIM users as shown in Figure 13 [2]. Accordingly, we have described and quantified the contribution of BIM-enabled DT and non-BIM DT studies to FM to these application areas as shown in Figure 14. It should be noted that in quantifying the percentages we have only considered those that are DT implementations and excluding those that were conceptual studies. In doing so, enabling technologies, and required data integration from building systems are also discussed in detail. To conclude, the correlation of integrated data sources and FM application areas implemented in DT studies is discussed.

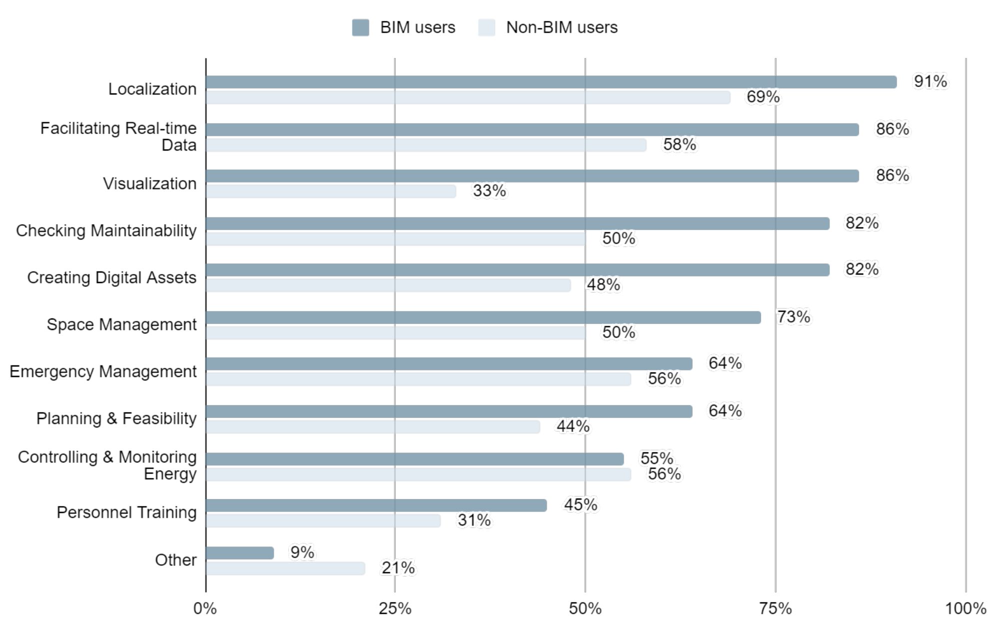

Figure 13 FM application areas for BIM [2]

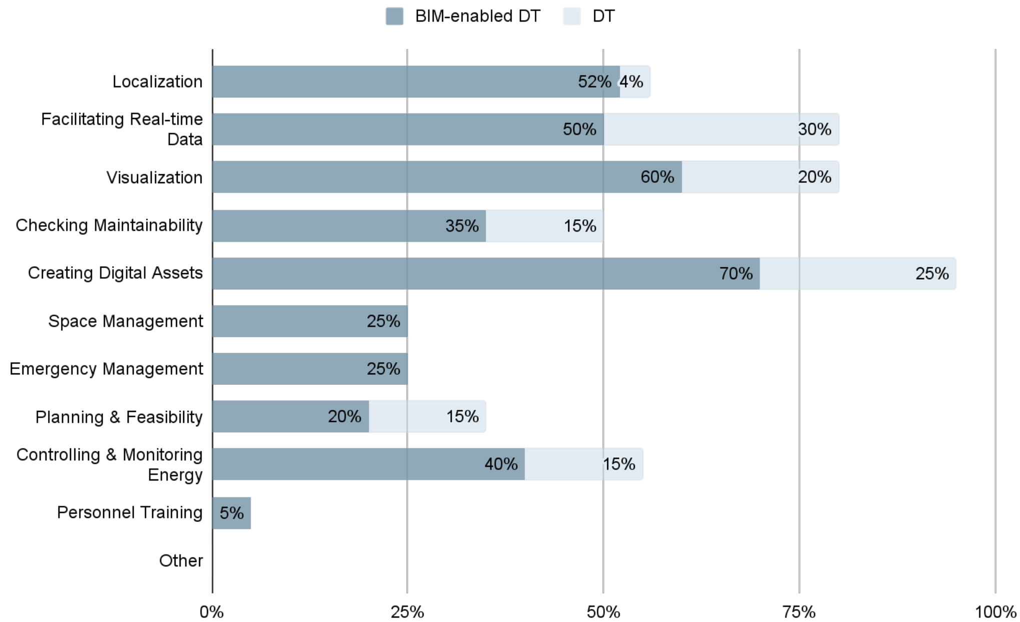

Figure 14 FM application areas in implementation original research

Information Management

Localization

Localization applications described in building FM use asset and occupants'/users' location information to support effective maintenance. Associating asset information with their location can help FM personnel in locating building equipment, people, and retrieving relevant information required for FM activities for example the maintenance information for an HVAC component. As shown in Figure 14, the potential of BIM use in localization applications had a high response rate from BIM and non-BIM users [2]. Accordingly, 93% of localization services described in the compiled literature (as noted those with DT implementation as original research) are from studies that have used BIM to create their DT as shown in Figure 15. This suggests the importance of BIM technology in facilitating localization applications in building FM.

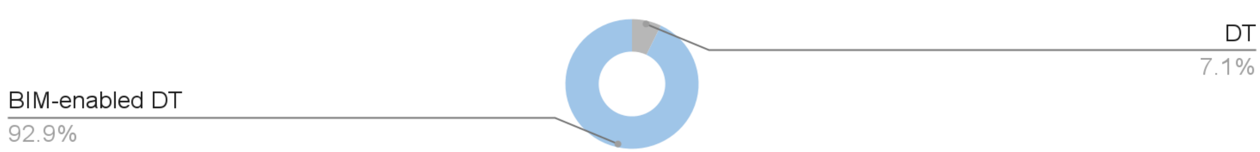

Figure 15 Frequency of localization applications

BIM models can provide navigation and visualization of asset information required to support locating building assets by FM personnel. Subsequently, studies that implemented localization applications have coupled several technologies with BIM to create DT representations with varied levels of fidelity. These technologies included captured images, AI, Bluetooth beacons, IoT and QR codes. For instance, Wei et al. developed a data integration methodology for updating as-is BIM models with captured facility images. They associated semantic data from the facility images with their corresponding BIM objects to help FM personnel locate and update asset information [48]. Although these corresponding BIM objects were perceived as DTs, the developed methodology facilitated data integration and the updating of digital assets for DT implementation that could be interpreted as a digital shadow defined by Kritizinger et al.

Additionally, localization services can facilitate timely inspections by FM personnel and help avoid costly repairs. To demonstrate, Peng et al. developed a hospital building digital twin that integrated data from Bluetooth beacons and QR codes with BIM for localization of FM personnel and assets. Their locations were then used to automatically assign time-sensitive repair tasks to the nearest workers as shown in Figure 16.

Figure 16 Locating the closest FM personnel for time sensitive repair orders [28]

Finally, localization applications can support assessment of asset changes and user experience based on their location trajectories. For example, Moretti et al. developed a 3D digital model that integrated BIM, GIS, and condition assessment (CA) data to support the creation of a digital twin for a complex of buildings. Similar to Wei et al. they associated captured images of facility assets with their corresponding BIM objects. They were then stored in a central database and integrated with location data from GIS. Finally, FM personnel were provided with a CA score and location data for assets through a visualization interface. This context helped FM personnel answer questions such as why one room's paint was deteriorating faster than another. In a different study, Angelieu et al. developed a digital twin for structural health monitoring of historic buildings that supports preventive maintenance. They used sensors and 3D point clouds to assess damage to iron ties in the historic building of Milan Cathedral. Deteriorations were automatically detected through AI algorithms and based on their location the severity of the damage was assessed. The DT prompted their substitution if required and adjacent structure that may be affected was also highlighted for FM to locate.

In a non-BIM DT study, Centorrino et al. used localization to enhance visitor experience and support the preservation of artwork in a museum [31]. Overcrowding in museums can cause changes in temperature and humidity levels that affect artwork. Therefore, to control visitor numbers, they distributed Bluetooth beacons to museum visitors to track their trajectories on an IoT-based tracking system. They then developed a digital twin using ML algorithms to reconstruct realistic visitor trajectories and optimize the museum's ticketing and entrance system [31].

Facilitating real time data access

The physical to virtual connection is an essential part of DT that is often defined through a live connection or real-time data access. Suitably, 80% of original implementation studies facilitated real-time data access to establish their digital twins as shown in Figure 14. Examples in the compiled literature demonstrate how a live connection can support feedback from DT services. Services including visualization, monitoring, and anomaly detection provide FM personnel with feedback required to carry out various FM functions. In several higher fidelity studies, real-time data was used to enable both feedback and control services to establish a digital twin as shown in Figure 17. In our classification of digital twins, FM predictive services such as preventative maintenance were considered as examples of automation. Thus, a change in the virtual entity of DT induced or resulted in a change in the physical entity through predictive anomaly detection and alarming systems.

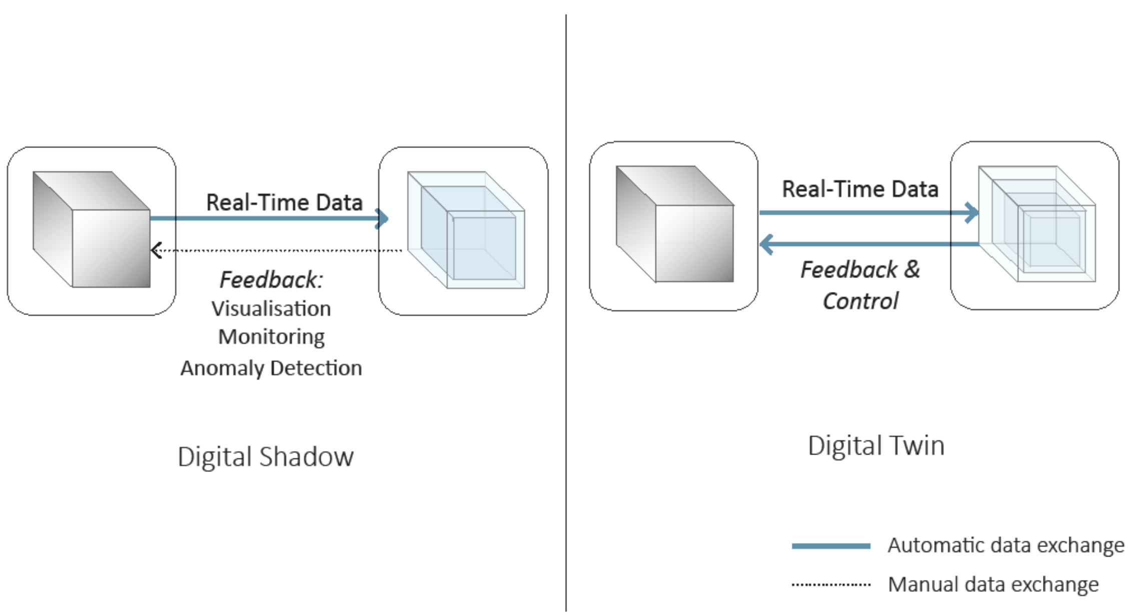

Figure 17 Feedback & Control enabled by real-time data

Moreover, 40% of DT studies facilitating real-time data were by non-BIM DT studies as shown in Figure 18. Compared to the other applications, this is the highest implementation rate by non-BIM studies.

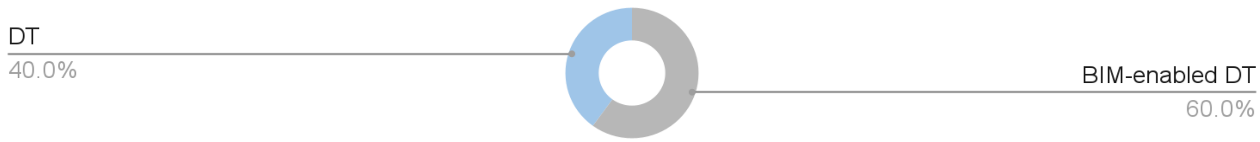

Figure 18 Frequency of facilitated real-time data access applications

Khajavi et al. explains that all buildings, including older ones that do not have BIM models, can benefit from real-time data [35]. Subsequently, they developed a methodology for establishing IoT-enabled sensor networks to build their non-BIM-enabled digital twin. Sensors were placed on a building facade and their data was stored in a cloud platform to monitor temperature, lighting, and humidity data. Color variations on a grid were used to represent different intensities from the lighting data on the building facade. Moreover, they described other potential applications for their DT such as adjusting indoor lighting based on outdoor levels and utilizing temperature variations to optimize the sourcing of heating and cooling [35].

In a more comprehensive DT study, Lu et al. detailed the development of a building DT in West Cambridge campus [39]. Facilitating real-time data access was described as part of the first two layers of a five-tier system architecture. First data from sensors was integrated with the DT as part of the Data Acquisition Layer along with data from the building, asset, and space management systems. Next a wireless sensor network (WSN) was established in the Transmission Layer linking sensor data and the other data sources to DynamoDB cloud database. Finally, the Data Integration Layer integrated data from the DynamoDB with the as-is BIM model from the Digital Modeling Layer to support DT services. As a result, Lu et al. achieved visualization, monitoring, anomaly detection, and forecasting for building assets and maintenance procedures. This information supported FM decision making and preventative maintenance of building assets and user activities.

Visualization

A collaborative digital twin platform can integrate multiple FM systems, people, and their locations into a visual interface for performing DT services and receiving feedback. Information visualization is a key part of the DT platform that supports decision making in FM. For example, Lu et al. developed a building DT with a DT platform to support FM activities and stakeholder collaboration. The DT platform is based on extracted IFC files to take advantage of BIM's visualization capabilities. Moreover, it was developed using a cloud database and API web service capable of visualizing monitored and feedback data in an intuitive way [37]. In a non-BIM study, Khajavi et al. created a DT that visualized real-time light intensity values on a building facade as described in the subsection on localization. Darker shades of yellow represented low lux values while lighter shades were assigned to higher lux values [35]. In a higher fidelity application, Peng et al. developed a DT control center with a 2.6 x 4.7-meter screen for a hospital building. The control center visualized building facilities, their status, and DT feedback using static data from BIM models, live data from IoT devices, and AI simulations facilitating access to assets and user interaction.

In a different study, Moretti et al. used a commercially available DT platform named Cesium to support their 3D digital model. As described above Moretti et al. developed a model that integrated BIM and GIS to support the creation of a neighborhood digital twin [43]. This interface was intuitive even for inexperienced users. Like the DT control center described, the bespoke 3D interface included real-time visualization of reports and maps related to asset inspection. Moretti et al. described the interface or platform as providing “different granularity in the data visualization” which provided reliable and collaborative information visualization to multiple users as needed [43].

Maintenance Management

Checking Maintainability

DT applications for checking maintainability are critical for optimizing performance [38]. Anomaly detection of monitored data and prompt inspection of building assets in FM can help reduce costs related to their failure or other operational inefficiencies. For instance, Lu et al. developed an inspection system for the anomaly detection of two pumps as part of a building DT funded by CDBB. The system was based on real time data from sensors on the pumps and automatically triggered an alarm for abnormal behavior. Lu et al explains that this is because the pumps were considered critical assets and suggests that other assets be indirectly monitored through temperature data [37]. In a similar study, Lu et al. developed an AR-based inspection system to support the same building DT (Lu et al. have developed a DT for a building and studied different aspects of this DT in different studies). They monitored temperature abnormalities and linked them to corresponding failed assets in the as-is BIM model. Tasks related to the failure would then automatically be assigned to FM personnel. The AR-based system highlighted failed assets to support localization and timely inspection by FM personnel [38].

Creating & updating digital assets

DTs have often been described as data-driven or built on data because they integrate data sources from various software systems [37]. This helps reduce redundancies and overlapping data scattered across systems. IFC-based data structures can facilitate the matching of asset data with their corresponding BIM objects. For example, if a building asset is replaced, its new ID number in the asset management system automatically triggers an update in the BIM model [39]. This supports a single truth model and timely FM search by eliminating system redundancies. Moreover, access to shared and reliable data can support informed decision-making in FM. Lu et al. achieved task prioritization by enabling user-updates on building assets through mobile app Itemit 2019. Users could scan asset tags to access visualized information on their current condition and comment on any repair issues. Finally, ML algorithms applied on historical repair data were used to prioritize maintenance tasks and give feedback on response times [39]. Moretti et al. also emphasized data integration and interoperability for prioritizing building components. Compared to Lu et al, they integrated BIM and GIS with condition assessment data from manual expert assessment rather than real time data [43]. Overall, prioritizing maintenance tasks can help save unnecessary costs in FM.

Space Management

Space management applications have only been described in BIM-enabled DT studies in the literature. BIM models contain important static data such as building geometry and space division that support consistency in DT [28]. Furthermore, DT space management services are enhanced through the integration of dynamic data related to space utilization with BIM's visualization and data management capabilities. This is shown in a study by Antonino et al. where space schedule data was used to optimize maintenance plans [27]. They updated an office building BIM model with real-time occupancy schedules from image recognition sensor data using Revit DB link and stored in Microsoft Azure SQL Database. Cleaning services were then determined based on real-time occupancy rates and cleaning costs were reduced by 45%. In a similar study, Lu et al. used a cloud-based space management system and database called MiCAD to visualize and manage room allocations in an office building based on real time occupancy data [39]. Additionally, statistical analysis of space information enables efficient room allocations and optimized space use [39], [28].

Planning & Feasibility Studies for Noncapital Construction

Planning and feasibility studies in facilities management can help evaluate the success of non-capital construction such as renovations, improvements, and installation of new equipment or technology. This application area can also be used to evaluate the implementation of digital twin technology. For example, the Digital Twin Concept (DTC) discussed in Section 2 sets objectives and requirements for DT implementation during the planning phase. In the context of facility management, we can consider this to be the planning of new equipment and technology. The DTC can include studies such as market analyses, user needs, operation and control strategies, and virtual model requirements that can help achieve the desired benefits from the DT. As shown in Figure 14, only 35% of studies from the compiled literature discussed planning and feasibility applications. Subsequently, Peng et al. had consultants evaluate their DT for a hospital building and they recommended future planning and feasibility studies on the financial risk and benefits of implementing DT. As demonstrated in their study, DT implementation in FM requires extensive infrastructure for wireless sensor networks (WSN), cameras, and visualization platforms. Not only can these technologies be difficult to implement in existing buildings but require large investments. Love and Mathews addressed this gap in feasibility studies and developed a business dependency network (BDN) to assess the capabilities of DT technologies before implementation. Their research focused on asset management for industrial projects including a railway, an oil refinery, and other plants. However, their findings show increased productivity and cost savings encouraging the use of benefits management for DT implementation.

Personnel Training & Development

DTs manipulate large amounts of data which can be visualized and modified through a single platform. Visualization capabilities of the DT platform help FM personnel grasp a detailed view of the state of the building. Additionally with the use of AI and ML various FM activities can be automated reducing their workload and increasing efficiency. For example, Wang et al. developed a DT - Green Building Maintenance System (DT-GBMS) to sustainably support FM personnel in their activities [47]. To demonstrate, they developed a prototype on Asset wise platform that integrated virtual models developed from 3D point clouds with real-time data from twenty sensors. The visualized platform provides access to real-time and updated building information that fosters understanding for FM personnel. Additionally, DT-GBMS applications such as monitoring, anomaly detection, and failure prediction automate various FM functions, reducing errors and manual labor by FM personnel. However, FM still includes many traditional practices and implementation of new technologies can require personnel training especially in specialized buildings. Therefore, before starting operation of a hospital building DT, ten FM personnel were assigned training for DT management. Additionally, a DT consultant group was involved in the project from the early design phase and assisted in training the remaining FM personnel during operations [47].

Energy Management

Controlling and monitoring energy is an important application in FM that significantly impacts building costs and emissions. Energy management includes mechanical, electrical, and water consumption in buildings which can be monitored and regulated through computer-aided control systems. For example, FM personnel can control lighting, power systems, HVAC, and water through building management systems (BMS), asset management systems (AMS), and space management systems (SMS). Several DT studies have integrated sensor data from these systems with BIM and AI or ML to automate FM applications in monitoring, anomaly detection, and preventive maintenance of relevant energy assets. However, automated feedback from these applications still required FM personnel intervention. For example, DT interfaces with real-time data integrated from BMS, AMS, or SMS could automatically detect abnormal behavior of assets and notify FM personnel. This encouraged timely inspection, repair, and prevented any further energy waste resulting from the abnormal behavior.

Emergency Management

Digital twins' potential for emergency management applications has been conceptually discussed in the compiled literature. Through the collection of real-time data, DTs' space management and visualization capabilities can support users in identifying the optimal path to safety. Rescuers can also perform interrogative services to know how many users are in the building, locate and plan for their rescue [27].

Table 3 below describes the capabilities and data requirements of commercially available DT solutions described and implemented in the literature. Data integration is a key part of these web services in which interoperability plays a major role. Several of the DT platforms described are provided by well-known vendors Bentley, Microsoft, and Autodesk as shown below.

Table 3 Commercially available solutions for establishing DT platforms

Name	Vendor	Capabilities	Interoperability	DT Definition
AssetWise - for advanced infrastructures	Bentley	• Connected data environment • Navigate virtual models • display real-time and historical data. • Modify and update asset information.	• Asset management: Infor, IBM Maximo, Oracle, etc. • Document management: Sharepoint,	"A realistic and Dynamic digital representation of a physical asset, system or city." [53]

Name	Vendor	Capabilities	Interoperability	DT Definition
		• supports asset life-cycle management. • Monitoring and anomaly detection through user-defined thresholds. • Failure Prediction	Documnetum, etc. • 2D/3D design: OpenPlant, AutoPlant, etc. • IoT platform: Mindsphere • Esri • ISBM standards	
Azure DT- for buildings, factories, farms, energy networks, railways, stadiums, and cities	Microsoft	• IoT based platform for creating self-defined DT architecture with open modeling language- DT Definitions Language • Provides live visualization and advanced query and simulation capabilities.	• Asset management including IoT devices using Azure IoT Hub, Logic Apps, and REST APIs	“Azure Digital Twins is an Internet of Things (IoT) platform that enables you to create a digital representation of real-world things, places, business processes, and people. Gain insights that help you drive better products, optimize operations and costs, and create breakthrough customer experiences.” [54]
Portal- for facilities and infrastructures	ecodomus	• Cloud platform for BIM-based DT based on Cobie extensions • Document management • 2D/3D visualization • asset management • data quality control • issues management.	• Common data environment ISO 19650 compliant • Open standards: OPC, MQTT, BACnet, etc. • Integration with Maximo, SAP, etc.	“Ecodomus software helps create virtual replicas of facilities and infrastructure, Digital Twin, via integration of BIM / SCADA / IoT / CMMS/ ERP / GIS and other systems.”[55]
Tandem- for the AEC industry in beta	AUTODESK	• Tracks changes across applications like Revit or excel. • Asset integration and clustering • Visualization dashboards with summary views and color coding • Global search with filtered datasets	• Open APIs • Owner specified data requirements through Tandem Facility Templates • Integrates data from Revit, BIM 360,	“A digital twin integrates real-time data from a built asset with its digital representation to create insights across the project lifecycle.” [56]

Name	Vendor	Capabilities	Interoperability	DT Definition
		• Facilitates digital handover	CMMS systems and others.	
Cesium ion- for global terrain, imagery, and buildings	CESIUM	• Creates 3D tiles • Cloud hosting and built to scale • Advanced analytics through Cesium ion SDK • Web visualization through Cesium js	• Cesium JavaScript runs across devices • Open source and free	"...digital twins contain vast amounts of geospatial data, but they are updated in real time with live information from an array of sensors, and they use AI, simulation, and machine learning to support decision making"[57]

Summary of Findings

Benefits of DT implementation for FM applications described in this section can be summarized as follows:

- Integrated platform with shared access to all information
- Improved accuracy & reduced errors
- Time and cost savings
- Stakeholder communication and collaboration
- Advanced decision-making, based on real-time data, and considers various factors from integrated database
- Effective data and information management
- Less training required, and less personnel

Of the collected original research implementation studies 42% used four or less applications and 42% used five to seven applications. However, only 16% used eight to ten applications. Compared to other studies they used extensive data integration of multiple building systems through combined technologies. Therefore, we identified the amount of data sources integrated from building systems for each application. In Figure 22 below we show the correlation between application areas achieved and the amount of integrated data sources described in the literature. Studies have integrated different numbers of data sources to achieve the same application area. However, as described in this section and as shown in Figure 22 (to be recreated), higher levels of fidelity can be achieved through data integration.

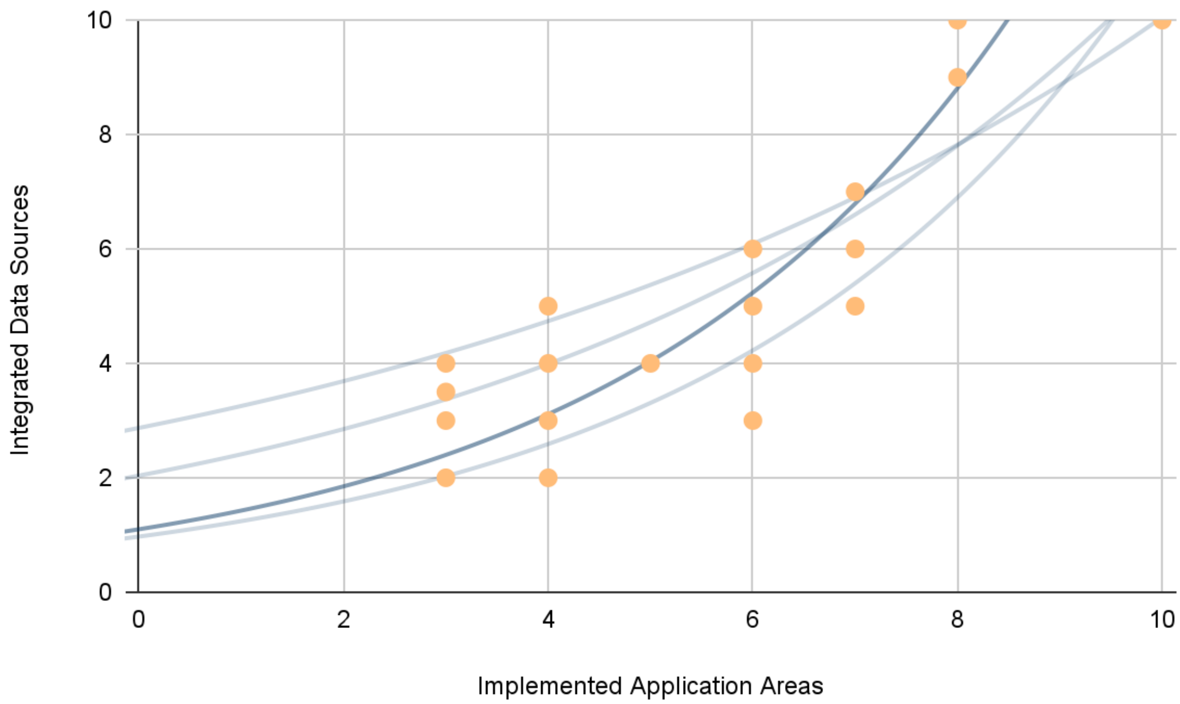

Figure 19 Integrated Data Sources and Application Areas

Gaps and Challenges in DT Applications

In keeping with the previous section, the above-mentioned FM application areas were used to evaluate DT challenges and gaps from the compiled literature. Furthermore, challenges in BIM implementation for each FM application area were compared to those of DT. Table 4 presents a bulleted list of challenges related to BIM on the left column and DT on the right.

Table 4 Bottlenecks of FM applications for BIM compared to DT.

BIM	DT
Localization	
● relies on transceivers transferring the data in the context (comes from BIM) of localization, which are not readily available in BIM models ● Linking BIM to FM databases to associate located equipment with its specifications and maintenance history	● difficulties in localization accuracy and finding suitable training data for extracting semantic data [48] ● Lack of indoor localization techniques for AR use [38] ● Failed to automatically highlight assets in AR environment [49] ● Noise from Bluetooth signal [31]
Facilitating real time data access	

<table>
<tr><td>Require semantic data integration with BIM
Requires big data storage
Typically, not updated during FM, static data from as-designed BIM model</td><td>Data storage, data integrity, validity, and interoperability. Single source data cannot provide holistic view, need to monitor multiple indicators/ data sources. This is difficult to achieve given likely budget constraints. Need to strategize. i.e., linking temperature anomalies to failed assets. [37]
Establishing wireless sensor networks:
Noise from sensors, i.e., varying lighting data from adjacent sensors [35], [37]</td></tr>
<tr><td colspan="2">Visualization & Marketing</td></tr>
<tr><td>Lack of collaboration & model utilization</td><td>Lack of DT platforms
Need to be more user-centered and intuitive</td></tr>
<tr><td colspan="2">Checking Maintainability</td></tr>
<tr><td>Could be enhanced through updated status of assets and documents which requires real-time data.
Requires experienced FM experts for decision making [37]</td><td>Fragmented building data sources [37]
Advanced data analysis [28]</td></tr>
<tr><td colspan="2">Creating & updating digital assets</td></tr>
<tr><td>Lack of collaboration & model utilization
Interoperability, difficult to integrate into one platform:
Associating correct data and documents from different data sources: main challenge
Need to identify non-geometric data requirements for FM:
Proper nomenclature and organization
Lack of vendor support: rfid, QR codes, etc.
Roles and responsibilities for updating assets</td><td>Interoperability of building systems. i.e., Cobie does not facilitate real-time data integration
Associating semantic data with BIM objects: lack of research on IFC extensions based on FM activities. Require expert experience to define integration strategies [37]</td></tr>
<tr><td colspan="2">Space Management</td></tr>
<tr><td>Difficult to integrate real-time occupancy and environmental data relevant to space utilization.</td><td>Data storage, especially from heavy point clouds.
Unique spatial arrangements, difficult to automatically capture and digitize.
Includes static data that does not require real-time updates.</td></tr>
</table>

Planning & Feasibility Studies for Noncapital Construction	
• Need for investment: training, software, infrastructure • Lack of adopting new technologies • Undefined fee structures for additional scopes • Lack of proof of positive return on investment	• Requires data collected from implemented DTs. • Lack of DT platform capable of multivariable simulations/ DT aggregate. • Lack of benefits management strategies.
Emergency Management	
• Beyond egress analysis, could be expanded to account for real-time management of an emergency situation through navigation and situational awareness. If we look at this dimension, then BIM tools are not sufficient.	• Difficulties in achieving accurate localization and real-time space management data.
Controlling and Monitoring Energy	
• Redundancy and repetitive data in BIM and BAS systems with inconsistent graphics • Require interface that can integrate BIM with BAS networking protocols. Control and monitoring require a mapping between sensor and actuation data. • Less developed compared to other applications	• Control of energy consumption was not automated; tasks were assigned to FM personnel. To achieve control additional costly 'debugging' was required. • Data security: had to convince owners to share certain data. "DT systems should only visit private cloud HTTP APIs inside hospital firewalls"[28] • Data standards for diagnosis models
Personnel Training & Development	
• Advanced training for operating FM systems in conjunction with BIM.	• Requires software, equipment, and technology installation and upkeep by FM personnel.

Overall, the compiled literature shows a lack of comprehensive implementation and quantified benefits from DT-enabled FM. Data has been described to be at the core of DT and large amounts of it are collected, stored, and analyzed to support FM applications. Accordingly, most DT challenges stem from issues in data integration. Not only are there diverse building types such as offices, museums, and hospitals but they individually include diverse management systems, software, and vendors with different data formats. Given the lack of standardization, many of these data formats are noninteroperable and create major bottlenecks for data integration in DT. For example, BIM provides data management capabilities and a vast amount of information required for DT-enabled FM. Nonetheless the BIM model must be updated with data from FM systems such as asset management systems (AMS), building management systems (BMS), and space management systems (SMS). These systems then need to be updated with data from diverse sensor types, cameras, and laser scanners. Consequently, several studies have contributed data association methodologies for updating as-is BIM models with images and 3D point clouds further detailing their challenges. However, less studies have used BIM to facilitate real-time data compared to other application areas. This could be attributed to their lack of interoperability and large amounts of data collected by DT.

A few higher-level DT studies achieved data integration through APIs used to build DT platforms or interfaces but faced other challenges. DT applications such as checking maintainability or controlling and monitoring energy require the simulation and manipulation of multiple variables. Hence the lack of a configurable and commercially available DT platform with prediction and control capabilities is yet another bottleneck. Therefore, most studies have not been able to achieve a comprehensive DT for FM applications. Other less discussed challenges that also need to be addressed include cyber security and manmade disasters or threats.

Discussion

Digital Twins for building facilities management need to address diverse facilities and their complex functions including different systems and unique requirements. Their ability to integrate data from equipment and systems with different software, vendors, and data formats into a single platform is critical. Furthermore, with the application of AI and ML algorithms multiple sets of information can be manipulated to enhance FM functions. While human intervention is typically excluded in DT definitions it is described in most FM applications. A variety of factors influence the level of automation described in DTs for building FM. For example, automated control can introduce privacy and safety concerns for some critical buildings such as healthcare and government facilities. Therefore, digital shadows may be better suited since they lack the virtual to physical connection but can still provide the precise maintenance required through visualization, monitoring, and feedback capabilities. Meanwhile, non-critical buildings such as offices may benefit from automated control functions for lighting and HVAC. Other non-critical buildings such as single-family homes might not benefit from functions beyond monitoring. Similarly, DTs can have different priorities such as safety, energy, cost savings, or thermal comfort that can require different levels of data granularity. Research on buildings with similar functions and systems such as chain retail stores or school systems could help establish these requirements. More research is also needed on the financial investments of DTs in building FM and their return on investment. However, this may be difficult to achieve given the diversity, complexity, and lack of data availability in buildings.

As discussed in the literature review section the study excludes papers on BIM in FM that may describe digital twins but do not use the term. This study focuses on studies that use the term 'digital twin' to identify how different authors have perceived the DT concept. However, this is a limitation of this study as it excludes papers that discuss DTs but do not use the term 'digital twin'. Including additional terms such as 'BIM' and 'human-in-the-loop' for building FM could give better insight into DTs. Additionally, there may be existing DTs that could be explored through expert and industry professional interviews or surveys.

Conclusion

This study explored existing DT applications in building facilities management and their characteristics as well as technologies used to establish them. With the aim of characterizing digital twins in building FM, four major categories were described: DT origins, three levels of integration between the physical and digital spaces, a five-dimension model centered on data, and finally the Gemini principles unifying the UK's efforts to create a national digital twin. Real world building facilities management is complex and includes various fields and large amounts of data. DT applications in FM aim to optimize these complex functions in an intelligent manner that allows for reasonable amounts of data to be exchanged. BIM has achieved many DT requirements through its visualization and data management capabilities. When BIM is integrated with additional FM systems and IoT it begins to resemble a digital twin by displaying the buildings behavior and updating in real-time. However, AI and ML are key aspects of DT that allow for the optimization of FM applications. ML algorithms can find logic and patterns in large amount of building data and help automate FM functions that previously relied on expert knowledge. Furthermore, with data integration and a unified DT platform can provide a single truth to previously scattered and redundant data across FM systems.

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