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Evaluation of Digital Twin implementations in Facility Management – A systematic review

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Evaluation of Digital Twin

Implementations in Facility Management – a systematic review

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Abstract. Digital twins have found increased interest in the recent years with articles being published at an increased rate in the years 2018-2020. with digital twins it is possible to achieve an efficient and responsive planning and control over of facility management. A digital twin by JTH has been implemented for some of the rooms in a corridor, a structured literature study is performed to bridge the knowledge gap, the aim is to review scientific literature regarding digital twins' in facilities management and assess different concepts digital twins in facility management. The method used is a mixed qualitative-quantitative systematic review that follows the Preferred Reporting Items for Systematic Reviews (PRISMA). The systematic review defines digital twins in facility management and identifies categories as well as digital twins applications in facility management and how digital twins can be used to evaluate building performance and room experience.

Keywords: Digital Twin, Facilities Management, FM, Internet of Things, IoT, BIM, Building performance, Evaluation, Built Environment, Occupancy Experience, Room Experience, Predictive maintenance, Error detection.

1 Introduction

1.1 Background

Digital Twin (DT) was first used by Aerospace and Manufacturing sectors, NASA defined a digital twin as a realistic digital presentation that combines data describing the physical asset with, processes and systems in digital format and due to the benefits of reducing costs, increase in performance, productivity, efficiency and readability, its application expanded to the architectural, engineering, and construction (AEC) sector for the facility management of buildings [1]. The concept of digital twins requires three parts: the physical product, the virtual replica, and what links them together in the form of an Internet of Things (IoT) which collects data through the internet of things and sends it to the virtual replica in the database and vice versa for optimization [2]. The digital twin of buildings is where a digital replica of a building is used for representation of a building which includes structures, spaces, conditions, and other occurrences such as flow of movement and so on. There are misconceptions that a 3D building information model is a digital twin but these usually lack the real-time flow of information. The purpose of a digital twin is to simulate an object in real-time using sensors that send data back to the digital model [3]. By integrating new technology such as the internet of things, building automation systems, user systems, facility management systems and so on enables the feeding and tracking of real-time data into analyzing and monitoring systems [3].

Digital Twin has found increased interest in recent years with the number of papers published about digital twin research in the architecture, engineer, construction, operation, and facility management (AECO-FM) industry between 2013 and 2021 has seen a sharp increase in 2018, 2019 and 2020 this trend shows that there has been a growing interest in digital twin research for the AECO-FM industry [4].

"Facility Management is an integrated approach to operating, maintaining, improving and adapting the buildings and infrastructure of an organisation in order to create an environment that strongly supports the primary objectives of that organisation" [5]. The digital twin can be used for facility management by feeding relevant information such as number of occupants in a room, energy usage optimization and so on. The digital replica's visualization is used for more complex tasks such as when a facility manager wishes to see the entire building [3]. The goals of using Digital Twins in the FM phase is to provide a platform to optimize structure related operational processes and seamlessly provide useful information to stakeholders [6]. The value of digital twins can be presented in operational and maintenance phases, for example a digital twin can monitor and adjust heating, ventilation and air condition settings without human interaction, automating and optimizing the process. In the operational phase it might be possible to improve how processes can be enhanced with virtual data, for example identifying what maintenance tools or parts are required before starting the maintenance process. It is also possible to use a digital twin as a tool for the building's lifecycle management going through alongside the physical counterpart the phases of design, construction, operation-maintenance and demolition [3]. The AEC industry has seen a rise in the adoption of Digital Twins technologies due to their potential in enhancing collaboration and information communication throughout a project's lifecycle, from design to operation and maintenance phase however the adoption is fragmented particularly in the case for Facility Management. With Digital Twins it is possible to achieve efficient and responsive planning and control of Facility Management activities by providing real-time status of building assets through Internet of Things sensors connected together as well as a 3D BIM Model [1]. As FM is worth up to 85% of the building's entire life cycle cost, efficiency gains become crucial for cost containment and building quality preservation [7].

1.2 Problem formulation

The aim of the thesis is to review scientific literature on Digital Twins in facility management and DT's usability in facility management. The objective is to identify gaps in the literature and assess the different concepts of digital twins in facility management. The literature study will be used to map different assessment approaches for digital twins in facility management as well as how to evaluate rooms in terms of comfort and experience and the result would be used to evaluate and develop the digital twin implementation at JTH in the future.
To achieve the aim of the study, research questions have been formulated to guide the literature study.

1. How can digital twins be defined in facility management?
2. How can digital twins be categorized in facilities management?
3. How can digital twins evaluate building performance and room experience comfort?

2 Materials/Methods

Quantitative research is the systematic empirical investigation of quantitative properties of phenomena and their relationships and involves measurements of some kind while a qualitative review is an in-depth enquiry to understand the meaning of phenomena and their relationships [8]. The method is a mixed qualitative and quantitative systematic review to gain an in-depth understanding of the subject, to collect articles and study them in-depth. A systematic review is a "review of existing research using explicit, accountable rigorous search methods" [8]. To ensure quality assurance of reviews it is recommended to follow quality assurance procedures. The literature study follows the Preferred Reporting Items for Systematic Reviews (PRISMA). PRISMA is a formal systematic review guideline for data collection, where data is obtained from articles over a time period and is limited to peer-reviewed papers from databases [9]. According to [8] Prisma is an "evidence-based minimum set of items for reporting systematic reviews and meta-analyses" and can refer to it for guidance.

PRISMA has a checklist that needs to be followed referred to as PRISMA – Protocols (PRISMA – P). The PRISMA checklist consists of 7 sections that are divided into 27 (item) topics. The checklist also has a location where item is reported for each item. The 7 sections are Title, Abstract, Introduction, Methods, Results, Discussion, and Other Information. The PRISMA 2020 items are also relevant for mixed-methods systematic reviews [10].

2.1 Inclusion criteria checked

The articles that pass the inclusion criteria is about digital twins in the built environment in regard to facilities management, occupancy evaluation and room experience. The articles that do not fit in such as digital twins in manufacturing and factories as well as buildings in the construction phase are excluded. The literature study focuses specifically on digital twin in facility management for built environments but also studies that are not necessarily about facility management. The data is limited to peer-reviewed articles only provided by the databases Scopus and Web of Science. The search is within Article title, Abstract, and Keywords. The terms in each field contain terms that can be interchanged with each other. Search terms are “Digital Twin*” in the first field followed with the second field being AND “X” where X is going to be a term related to the questions to exclude data that does not involve the current question. The search is also be limited to only articles, excluding reviews. The collected articles are stored in EndNote to be categorized further.

2.2 Search strategy and Data collection checked

Search 1 is “Digital Twin*” AND (“Facilit* Management” OR “FM” OR “Smart Cit*” OR “Urban” OR “O&M” OR “Operation & maintenance” OR “operation and maintenance”)with exclusions such as english language only as well excluding certain subject areas see appendix 1 table 4.

The first search was made 2022-03-15 retrieved 209 results in Scopus and 218 in Web of Science, by using EndNote Online about 76 references were marked as duplicate. By using the databases’ tools to exclude subject areas the results are further screened. The Scopus search resulted in 159 meaning 50 records were removed through tools, and out of 109 the rest was human screening left 52 records. Web of Science had 142 records due to duplicates removal through endnote and 7 records were human screened leaving a combined total of 59 records.

The second search was made for room experience and building performance with the search string “Digital Twin*” AND (“Occupan*” OR “Comfort” OR “room experience” OR “building performance” OR “post-occupancy” and was done 2022-03-15 as well, the search retrieved 28 records where 6 were removed for duplicates, 9 were human screened leaving behind 13 records. A similar web of science search was made for search 2 which yielded 24 records where 16 were removed for duplications leaving 8 behind for screening of which 4 were removed leaving 4.

A third search was made for evaluation, optimization and “quali*” with the search string “Digital Twin” AND (“evaluat*” OR “quali*” OR “optim*”) and was done 2022-0-4-20. The search retrieved 499 results in Scopus where 21 were duplicates leaving 471 records, A similar search was made for Web of Science where 433 records were retrieved where 83 were duplicates leaving behind 350 articles. Out of those 799 were screened away leaving behind 29.

The records left were a total of 105 which would be retrieved. 99 out of 105 studies were successfully retrieved. Out of the 99 articles, 27 articles were assessed for eligibility while 53 were removed due to not being applicable to Facilities Management, 10 due to not being applicable to the built environment, 8 were removed due to focusing on construction and 1 was removed due to being focused on manufacturing leaving out a total of

The Prisma Flow Diagram visualizes the different steps such as identification, screening, eligibility and inclusion. The flow diagram also highlights what database was used, what search words, how many articles are received, how articles are screened, how many have been assessed for eligibility and finally how many are included in the literature study.

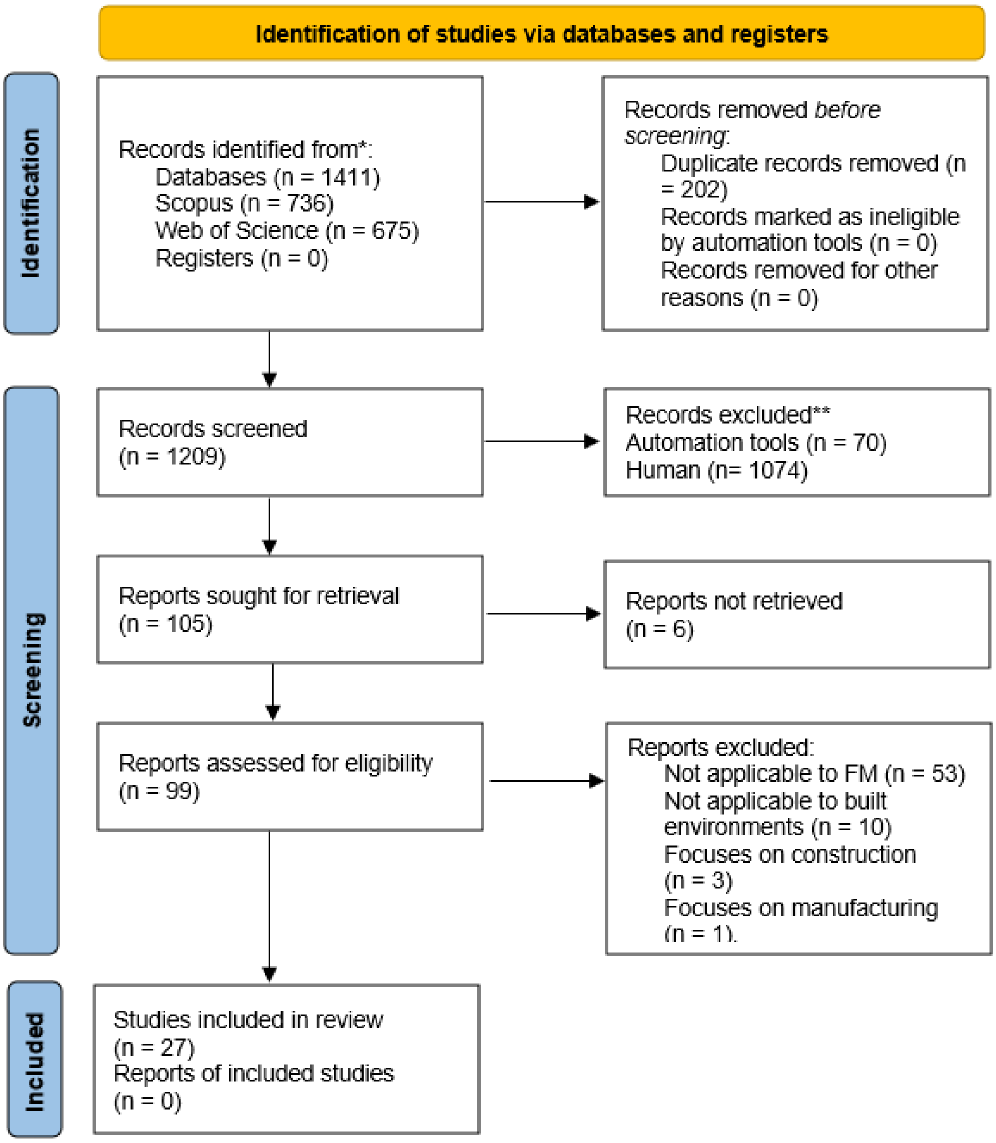

Figure 1. Prisma Flow Diagram

3 Results

The results will present the collected data from the chosen methods for the study. The chapter is divided into three parts that aim to answer their respective research questions based on the literature gathered, these are divided into sub-parts which go further into depth explaining each part. The first explains what a digital twin is and its subcategories the real part, virtual model and the link that offers real-time flow of information between them. The second part categorizes DTs in FM and explains applications and how they are used, the third part is divided into how to evaluate building performance and room experience.

3.1 How can digital twins be defined in facility management?

Table 1. Defining DT in FM

Research question 1	Relevance	Articles
Digital Twin	Basic explanation, Explain smart service,	Antonino et al., 2019, Camposano et al., 2019,
	Define DT	Daniotti et al., 2022, Hunhevicz et al., 2022, Lu et al., 2020,
	How DT improves FM	J. Zhao et al., 2022,
	How ML Is used in DT	Hosamo et al., 2022, Y. Zhao et al., 2022, Deng et al. 2021
BIM	Explanation of BIM, LOD and maturity level	Desogus et al., 2021, Godager et al., 2021 Seghezzi et al., 2021, Quirk et al., 2020, Wang et al. 2022., Zaballos et al. 2020
	How BIM contributes to DT.	Hosamo et al., 2022.
IoT	What sensor type and data collection	Antonino et al., 2019, Desogus et al., 2021, Fialho et al., 2022, Villa et al., 2021,
	Connection between IoT and DT	Hunhevicz et al., 2022,
	What programming language	Zaballos et al., 2020,

Digital Twins

Digital twins is a concept that is related to a physical structure's digital representation carrying real-time properties of the original structure [11]. A DT requires three parts, the physical part, digital model part and the part that links them together [2]. The concept of DTs evolved as a comprehensive approach to manage, plan, predict and demonstrate building assets with the DT being a dynamic representation of the asset and mimicking the behavior of the real-world asset [12]. Integration of real-time information and BIM develops a single source information known as a DT [13]. A DT needs to have a two-way flow of information, from real objects to the virtual counterpart and from virtual counterpart to the real side. When a digital model has a flow of information that is automated and one-sided from the real objects to the virtual objects it is considered a digital shadow, the virtual side does not send information back to the real objects, if there is no automated flow of information or if it is inserted manually then it is just a digital model [14]. DTs are seen as a key to enable smart services like such as smart maintenance by enhancing technical components in a building by mapping equipment that requires maintenance or through smart buildings which enable services such as monitoring and adjusting lighting and HVAC [15]. Machine Learning (ML) is integrated into the DT enabling smart services such as predictive maintenance by providing machine learning algorithms such as artificial neural network with input dataset variables. The real-time data that the sensors provide is fed into Artificial Neural Networks to who in turn supply the visual model with the predictive data for visualization (see Fig 1.)[16-18]. DT can help improve FM practices by enabling and improving real-time monitoring, maintenance, decision-making and cost performance [1].

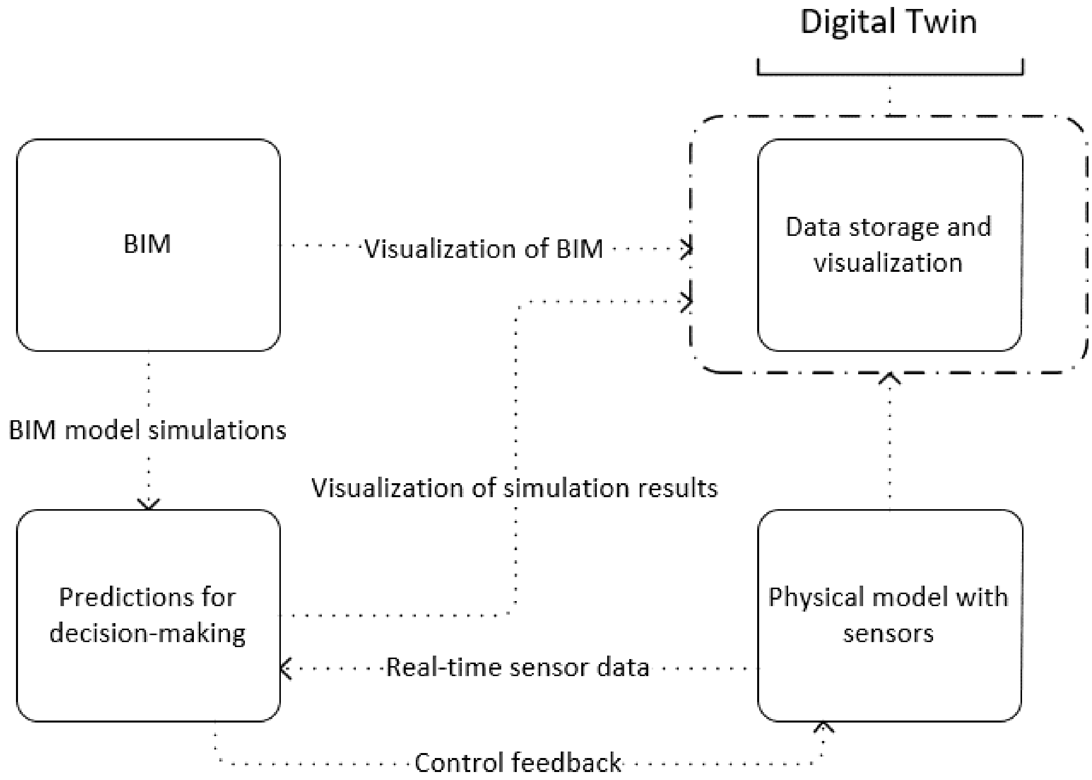

Figure 2. Ideal singular Digital Twin model according to Deng et al. 2021.
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Linkage
The internet of things (IoT) is what is used to connect this linkage between the physical model and digital model [2]. IoT is comprised of the network connecting physical objects to the internet and enables real-time understanding of buildings components and operations and through that improves the efficiency and quality of the data collected as well as the FM services [19]. IoT is defined as an ecosystem of smart objects with sensors and processing technologies that are integrated and work together to create smart services. [7]. Sensors are used to collect the desired data depending on what the DT is used for such as light collecting sensors [19], image recognition sensors for occupants [13], brightness, humidity, noise, voltage and current [20]. An IoT platform is used for the real-time recording of data from sensors and can be used for collecting, processing, visualization, and management of the data [20]. Different IoT platforms such as AWS IoT platform, Microsoft Azure IoT hub, IBM Watson IoT platform, Google IoT platform, Kaa IoT Platform, ThingSpeak, Carriots, Temboo, Thinger.io, and Sentilo all support different Data Formats and programming languages, most support JSON format while a few supports XML and CSV as for programming languages the majority support Java while others platforms also provide support for Python, C, .NET and other languages [21].

BIM
Building Information Models (BIM) are parametric models with centralized sources of information contained in them and are mostly for the design and construction phases and are instruments for improving collaboration and document management but the BIM model lacks the continuous flow of real-time data hence the need for sensors [22]. BIM models may contribute to facility management by serving as a repository for information to aid in planning and administration of building maintenance operations for both new and existing structures [16]. BIM has four maturity levels, from 0 to 3 which are used to determine to what degree a project is BIM-compliant [6]. BIM is used for the digital model part of the Digital Twin, a BIM model can be categorized by the level of graphical detail (LOD) and level of information detail (LOI) which measures how detailed the BIM model is [20] The level of detail depends on the modeling software, what use cases as well as time and cost [23]. In the case of only visualizing in 2D it is considered enough to go into a LOD of 3 and LOI of 6 for the monitoring of energy

consumption and indoor conditions[20]. The information that components use in BIM is defined in five levels, LOD 100 – 500, with LOD100 containing basic mass information of the building. LOD200 is the design stage and includes number, size, shape, position and direction of the building. LOD300 is a detailed design of the bim model and contains accurate data, LOD400 contains information for complete manufacturing, design, assembly, and detail. LOD500 is the model after completion and contains the buildings actual size, quantity, position, and direction.[24] For the case of predictive maintenance a BIM level of development of 500 is needed to create a predictive maintenance framework for air handling units [16]. Some BIM software can be used for visualization of data as well, Dynamo a part of Revit can be used for bridging the BIM model to the IoT platform and to link data collected from sensors [20, 21]. BIM can be considered the starting point of a digital twin acting as the semantically rich 3D model [25].

3.2 How can digital twins be categorized in facility management?

From the articles, digital twins are categorized through energy monitoring, energy savings, predictive maintenance, error detection, occupant detection, occupant prediction, comfort, and cost savings. The applications for digital twins in FM are described below (see Table 2.)

Table 2. applications of DT in FM

Research Question 2	Relevance	Articles
Comfort	Allows occupants to provide feedback for comfort	Abdelrahman et al., 2022, Daniotti et al., 2022
	Maintain comfort levels	Clausen et al., 2021,
	Monitors comfort levels	Desogus et al., 2021
	What to monitor to improve comfort	Martinez et al., 2021,
Energy Saving	Predict weather, occupancy prediction control over VAV,	Clausen et al., 2021, Zaballos et al., 2020,
	Aims to decrease net primary energy usage	Daniotti et al., 2022, Peng et al., 2021
Energy Monitoring	Decreases time for deep energy audits.	Daniotti et al., 2022,
	Monitors energy consumptions	Desogus et al., 2021, Peng et al., 2021, Zaballos et al., 2020,
Maintenance – Predictive Maintenance	Uses historical data to detect faults in Air handling units,	Hosamo et al., 2022, Peng et al., 2021,
Maintenance – Error detection,	Detect errors through performance variations in components	Fialho et al., 2022, Hosamo et al., 2022, Lu et al., 2020, Peng et al., 2021, Villa et al., 2021, Xie et al., 2020., Moretti et al., 2020.
	Detects building condition, rating the maintenance urgency.	Moretti et al., 2020,
Occupant - Detection	Detects occupants for spatial proximity	Abdelrahman et al., 2022, Clausen et al., 2021,
	What sensors are used.	Antonino et al., 2019
Occupant - Prediction	Predicts occupants	Clausen et al., 2021,
Cost – Cost saving	DT cleaning schedules save costs	Antonino et al., 2019
	VAV Dampener control	Clausen et al., 2021,
	Decrease renovation costs	Daniotti et al., 2022,
	costs and scalability between sensors	Lu et al., 2020
	Digital twin cost vs benefit risk	Peng et al., 2021,
	Post occupancy evaluation optimize implementation cost	Seghezzi et al., 2021,

Energy monitoring, saving and cost saving

By predicting occupancy, it is possible to save energy through lowering Variable Air Volume (VAV) damper position to zero when there are no predicted occupants in the nearby future compared to a rule-based damper which maintains a 45% damper position during operational hours, the energy savings were however unable to be quantified due to the natural fluctuation of both weather and room usage [26]. It is possible to save costs on cleaning services through occupancy detection, in office buildings not all offices are occupied for the entire day, by focusing on an occupancy-based cleaning service that activates after 16 hours of occupancy detected compared to a regular scheduled cleaning service [13].

BIM4EEB is a BIM-based toolkit for efficient renovation of residential buildings and focuses on implementing a BIM-based toolkit to be used during renovation of existing buildings to increase efficiency of information flow, improving building performances and comfort for inhabitants. The tool aims to reduce renovation time and average renovation cost, net primary energy use of residential buildings and time needed for deep energy audits [25]. A digital twin becomes viable when the cost of information inefficiency outweighs the cost of a digital twin, time saved finding information and detecting errors also play a factor [14]. Indicative Post Occupancy Evaluations (POE) can help optimize the implementation and lower cost of sensors by finding critical locations that need monitoring [22]. Digital twins can also collect data from renewable energy to compare with the energy consumption of the building [27]. Maintenance cost are around 65% of the annual FM cost, applying predictive maintenance can lower costs through higher efficiency and cheaper labor cost however lacks quantification [16].

While Digital twin uses such as predictive maintenance can provide opportunities to save costs and time through easy access to precise information provided, the costs of the components as well as maintaining and operating must be considered [19]. Financial risks are considerable when establishing a digital twin due to the large-scale construction of networks for sensors, cameras and wireless communicators [28]. Sensors, what data they collect, their reliability and their cost is considered first before being used in a digital twin as well as the installation cost and cost of software used and then compared to the cost saved [13]

Occupant monitoring

By using Model Predictive Control (MPC) algorithm enables optimizations by collecting occupancy count, location, and presence data through usage of dedicated Passive InfraRed sensors and counting camera sensors to predict occupancy [26]. Image recognition sensors can be used for measuring real-time occupancy data due to being able to provide information on location, count activity, identity and track at the same time compared to Passive InfraRed and ultrasonic sensors who might not be able to provide all the information and have higher installation costs [13]. It is possible to predict where occupants will be by feeding real-time data such as location, count, and presence into an occupant prediction model such as OccuRE [26].

Occupant detection and location is vital when taking into consideration the proximity of different building elements that may influence an occupant's thermal comfort such as windows and fans [29] while occupant prediction is needed to determine if a location needs to be ventilated as much [26].

Maintenance

Sensors capable of automatically detecting current and potential errors provide value to the maintenance process of buildings, by capturing different variations in building components' performance that would not be perceptible by humans [7, 12, 16, 19, 28, 30, 31]. 6 studies all use similar techniques and IFC in which they make use of sensors detecting variations and spikes in the components performance variations, with some of them using open source software[7, 31] Predictive maintenance makes use of historical data to capture the conditions of building components and predict failure or degradation of the building components [16, 28]. Building components such as smart lighting [19] or air handling units are examples of components with predictive maintenance [7, 16]. The data collected for the building components within the BIM model makes maintenance work more convenient by providing the locations of the failing component in real-time [7]. Error detection of thermal conditions can be improved through the usage of Augmented Reality to visualize thermal anomalies [30]. An openBIM approach can be made using IFC data containing geometric and semantic information, using an asset anomaly application and contextual anomaly detection algorithms such as Cumulative Sum (CUSUM) can be used to reveal anomalous behavior [31]. Air handling unit fault prediction in a hospital was made possible by using Long Term and Short Term Memory (LSTM) networks to track abnormal data changes over time [28]. Combining BIM and GIS (Geographic

Information Systems) into GeoBIM can help with monitoring the conditions of a building and assess whether building requires maintenance repairs [32].

Comfort

Comfort can be measured through thermal comfort and indoor air quality. It is possible to use digital twins to maintain comfort levels in an energy efficient manner through occupancy prediction and monitoring [26]. Occupant comfort levels can be decided through either occupant feedback [25, 29], through governmental criteria [26] or through emotion recognition software[21]. Monitoring CO2 levels, temperature and humidity can be used to establish air conditioning schedules and HVAC improvements, avoiding needs to open windows for natural ventilation and wasting thermal energy[20, 26, 33].

3.3 How can digital twins evaluate building performance and room experience comfort?

Table 3. Building performance and room experience

Research question 3	Relevance	Articles
Building Performance – Energy performance	Monitor energy consumption	Desogus et al., 2021
	Energy consumption and saving	Peng et al., 2021,
	LEED criteria and energy monitoring	Tagliabue et al., 2021, Zaballos et al., 2020
Room Experience – Thermal Comfort	Evaluate thermal comfort and proximity	Abdelrahman et al., 2022,
	Thermal monitoring	Daniotti et al., 2022, Tagliabue et al., 2021, Zaballos et al., 2020,
	VR thermal comfort visualization	Shahinmoghadam et al., 2021,
Room Experience – Visual Comfort	Monitor luminance	Daniotti et al., 2022,
	Monitors luminance, glare, daylight simulation.	Zaballos et al., 2020,
Room Experience – Air Quality	CO2 level monitoring	Tagliabue et al., 2021,
	CFD simulations and measures CO2 level.	Zaballos et al., 2020,
Room Experience - Feedback	Collects from feedback	Abdelrahman et al., 2022, Daniotti et al., 2022, Tagliabue et al., 2021,
	Emotion detection software and Indoor environmental quality	Zaballos et al., 2020

Building performance can be evaluated through DTs by monitoring the data provided by sensors, lighting and visual, energy performance through monitoring energy and energy saving, HVAC performance through thermal comfort and CO2. These can then be used in a certification system such as LEED or BREEAM [27]. Renewable energy such as solar power can also be monitored through DTs, combined with monitoring energy consumption can help optimize the trade-off between renewable energy production and consumption [27]. Room experience evaluation can also share similarities with a building performance such as thermal comfort

Certification systems can also help evaluate room experience such as LEED's Indoor Environmental Quality (IEQ) can be used to evaluate room experience or through previous literature studies' IEQs, these IEQ parameters have different weights to them through thermal comfort being the one with highest weigh to it, indoor air quality being second, acoustic comfort being third and visual comfort being fourth [21] these can bemeasured either through governmental criteria, such as the Danish Working Environment Authority [26] and through occupant feedback [25, 27, 29]. Occupants are given an opportunity to report their current comfort level regarding heat and sound is one way to measure occupant comfort while another is through criteria. Spatial proximity or nearness which refers to the area of impact or influence that an object has together with spatial-temporal data which is where an occupant is currently located can be used for improving occupant comfort [29]. Through BIM4EEB project, occupants whose building is undergoing renovation can give their feedback about comfort and activities through a web-based platform [25]. By integrating Virtual Reality (VR) enables real-time monitoring of thermal comfort conditions within a digital model of a building, enabling navigation through virtual spaces [34]. Emotion detection software can be used as a double check for perceived comfort, capturing faces of occupants with camera and using software such as “Microsoft Cognitive Services Face API” for emotion recognition [21].

Thermal comfort can be evaluated through subjective feedback, collecting data through web-based platforms[25], through applications installed in phones[27], or smart watches that allows occupants to give feedback if they are comfortable or prefer a warmer or cooler environment, occupant heartrate as well as near-body temperatures. The occupant’s location is also considered as proximity to different building elements such as windows, fans, air diffusers and heat sources which are given an Area of Influence which can impact the occupant’s satisfaction when providing feedback [29]. Other thermal comfort parameters can include humidity, occupant metabolic rate [21]. Acoustic Comfort can be evaluated through sound collecting sensors and standards from the International Organization for Standardization ISO 3382 with parameters including reverbation time, speech transmission index, level difference index, impact sound pressure level, sound clarity, and sound insulation. [21]. Indoor air quality can be evaluated through the measuring of CO2 levels [26] as well as air velocity and air change per hour through computational fluid dynamics simulations [21].

Visual & lighting comfort can be evaluated through daylight simulation, maintained luminance, and sensors that can detect glare, these can then be compared to standards such as European Committee for Standardization (CEN) or International Commission on Illumination (CIE) as well as occupant feedback. [21].

4 Discussion

4.1 Discussion

The articles all agree that DT in FM are divided into three parts: the physical, the virtual and that which links them together in the form of IoT and that the flow of information must be two-sided and in real-time. DT are used for different purposes in FM but are all seen as key to enabling smart services. The IoT is also seen in a similar light with sensors collecting data, differences in IoT platforms, programming languages and data formats complicates interoperability. BIM is seen as a repository for information and the digital model is used for visualization. Majority of the articles do not state what LOD they used for BIM only a few articles specified what level of detail they needed for BIM in DT, the differences in what the modeling software and purposes of the DT also affect what LOD is needed examples such as maintenance must specify what part of the model is malfunctioning which require a highest LOD for visualization. Machine learning is also considered part of the DT ecosystem where it collects information and outputs the predicted data into the ecosystem such as maintenance prediction where errors are visualized in the DT.

The categories of DT fall into Energy, Cost saving, Maintenance, Comfort and Occupant monitoring.
Energy saving and Cost savings share similar applications, this is due to energy saving results in reducing waste which therefore also lowers the costs that would’ve been spent on energy consumption or repairs although with one exception in cost saving, however some of the energy savings were unable to be properly quantified and the cost savings through predictive maintenance were not explained in depth either with mostly mentioning how maintenance can be optimized and time can be saved. Setting up a DT costs as well, meaning that the benefits of DT must outweigh the cost of a DT such as sensors and software needed to keep one running. DT in maintenance is mostly used for detecting and predicting faults in a similar manner, with fault detection focusing on deviation in component performance and fault prediction focusing on variations in component performance in both long and short term a few articles focus on visualizing anomalies through augmented reality, the articles regarding error detection had a plurality with 8 articles out of 27 being about detecting errors or visualizing anomalies through DTs. Comfort focuses mainly on maintaining thermal comfort with a few focusing on improving through occupant feedback and location of occupants.

DT can help evaluate a building’s performance through the real-time flow of data being collected for usage in a certification system such as LEED or BREEAM, reducing and monitoring energy consumption, indoor environmental quality and evaluating the real-time data using the certification systems. Room experience can also be evaluated through certification systems, through occupant feedback, thermal comfort, acoustic comfort, visual and lighting comfort, and indoor air quality all affecting room experience although at different levels, the articles studying room experience were mainly based on universities and campuses rather than residential buildings.

4.2 Knowledge gap

Although the studies have contributed to the advancement of Digital Twins in FM using new and novel methods, there does exist a few knowledge gaps that should be addressed to advance DT in FM further.

Size of the DT

Most of the DT frameworks used in the studies focus either on a single room or a single building with the exception of one study that made use of three different building sites. Using different building sites may lead discovery of new issues to that were not initially accounted for or how insight into how effective the DT frameworks can be when comparing between buildings.

Quantifying savings.

Some studies that utilize DTs are unable to quantify how much they possibly save on using DTs, a rule-based approach during default operation of ventilation and air handling units might prove better than a DT during high outdoor temperature and room usage due to building shape and buildings lacking dedicated cooling HVAC solutions as well as running the experiment for longer period. When regarding cost savings through cleaning intervention services, the study only projected the costs based on software and sensors as well as the savings of the cleaning service did not run for a full test to show a return of investment.

4.3 Limitation

A literature review using the PRISMA framework was conducted in this study to answer the following research questions regarding BIM, IoT and DT. A PRISMA flow diagram was used to visualize the identification, screening, eligibility, and inclusion of reports. Due to the strict criteria focusing on DT in the FM sector, a lot of reports were excluded from the study leaving the total reports collected less than 30. While DTs have existed for some time the topic of applying DT to buildings is relatively new but with has achieved an increase in interest in the recent years in the AECO-FM industry. The trending interest may lead to further studies in how DT can be used in FM and newer methods to help improve occupant comfort and building performance.

5 Conclusion

This study presented a review of DT implementation in FM. 27 papers were retrieved from different journals through 2 databases and were reviewed. The systematic literature review about scientific literature containing DT in FM and its usability in FM has been performed to assess the different applications of DTs in the context of FM, the systematic review has helped define said applications while addressing knowledge gaps and how those can be categorized. The applications were mapped to categories that DT in FM enables and how DTs can be used to evaluate building performance and room experience. A plurality of studies focused on maintenance error detections and predictions while the other studies focusing on thermal comfort, occupant monitoring and prediction and cost saving shared a more equal representation. Few studies focused on building performance and room experience but were more well-rounded and covered most of the subject.

As this study focuses on DT applications in FM, for future research it would be interesting to see what data format and programming language could prove to be the most beneficial for DT in FM, studies into how time saved, error detection and predictive maintenance can be quantified in comparison to the cost of a digital twin to justify the implementation of DT and further studies on how DT can help improve building performance and room experience, a research on creating new Key Performance Indexes to understand define how said improvement can be measured. Applying DT frameworks to different buildings and comparing them between each site would provide opportunities to find new issues that were unaccounted for, variations in how DT in FM's effectiveness due to different climate, outdoor conditions, and weather.

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Appendix 1 Search keywords and limitations

Table 4. Search keywords and limitations strings.

Scopus search 1.	(TITLE-ABS-KEY ("Digital Twin*") AND TITLE-ABS-KEY ("Facilit* Management" OR "FM" OR "O&M" OR "operation & maintenance" OR "operation and maintenance" OR "Smart Cit*" OR "Urban" OR "building lifecycle management" OR "lifecycle management")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English"))
Scopus search 1 limitations.	AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2018) OR LIMIT-TO (PUBYEAR , 2017)) AND (LIMIT-TO (LANGUAGE , "English")) AND (EXCLUDE (SUBJAREA , "EART")) AND (EXCLUDE (EXACTKEYWORD , "Manufacture")) AND (EXCLUDE (EXACTKEYWORD , "Industrial Research")) AND (EXCLUDE (EXACTKEYWORD , "Bridges")) AND (EXCLUDE (EXACTKEYWORD , "Intelligent Transportation Systems") OR EXCLUDE (EXACTKEYWORD , "Intelligent Vehicle Highway Systems")) AND (EXCLUDE (EXACTKEYWORD , "Supply Chains")) AND (EXCLUDE (EXACTKEYWORD , "Construction Process"))
Scopus search 2.	(TITLE-ABS-KEY ("Digital Twin*") AND TITLE-ABS-KEY ("Occupan*" OR "Comfort" OR "room experience" OR "building performance" OR "post-occupancy")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2018) OR LIMIT-TO (PUBYEAR , 2017)) AND (LIMIT-TO (LANGUAGE , "English"))
Scopus search 3.	(TITLE-ABS-KEY ("Digital Twin*") AND TITLE-ABS-KEY ("evaluat*" OR "quali*" OR "optim*")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2018) OR LIMIT-TO (PUBYEAR , 2017)) AND (LIMIT-TO (LANGUAGE , "English"))
Scopus search 3 limitations.	AND (EXCLUDE (SUBJAREA , "MATE") OR EXCLUDE (SUBJAREA , "PHYS") OR EXCLUDE (SUBJAREA , "CENG") OR EXCLUDE (SUBJAREA , "BIOC") OR EXCLUDE (SUBJAREA , "CHEM") OR EXCLUDE (SUBJAREA , "EART") OR EXCLUDE (SUBJAREA , "MEDI") OR EXCLUDE (SUBJAREA , "AGRI") OR EXCLUDE (SUBJAREA , "PHAR") OR EXCLUDE (SUBJAREA , "IMMU") OR EXCLUDE (SUBJAREA , "ARTS") OR EXCLUDE (SUBJAREA , "NEUR") OR EXCLUDE (SUBJAREA , "HEAL") OR EXCLUDE (SUBJAREA , "PSYC") OR EXCLUDE (SUBJAREA , "VETE")) AND (EXCLUDE (EXACTKEYWORD , "Manufacture") OR EXCLUDE (EXACTKEYWORD , "Smart Manufacturing") OR EXCLUDE (EXACTKEYWORD , "Product Design") OR EXCLUDE (EXACTKEYWORD , "Production Control") OR EXCLUDE (EXACTKEYWORD , "3D Printers") OR EXCLUDE (EXACTKEYWORD , "Machine Tools") OR EXCLUDE (EXACTKEYWORD , "Intelligent Manufacturing") OR EXCLUDE (EXACTKEYWORD , "Manufacturing Industries") OR EXCLUDE (

	EXACTKEYWORD , "Agricultural Robots") OR EXCLUDE (EXACTKEYWORD , "Additive Manufacturing") OR EXCLUDE (EXACTKEYWORD , "Manufacturing")) AND (EXCLUDE (EXACTKEYWORD , "Industrial Research") OR EXCLUDE (EXACTKEYWORD , "Manufacturing Process") OR EXCLUDE (EXACTKEYWORD , "Production System") OR EXCLUDE (EXACTKEYWORD , "Electric Vehicles"))
Web Of Science search 1.	https://www.webofscience.com/wos/woscc/summary/7b6cdf31-cfe6-4335-9d87-7dfdfadef7ce-2aaf91fc/relevance/1
Web of Science search 2.	https://www.webofscience.com/wos/woscc/summary/958a9845-7192-4abd-a2e5-688972d2ba9d-2aa63275/relevance/1
Web of Science search 3.	https://www.webofscience.com/wos/woscc/summary/dd2c734c-173f-45b0-9769-f6178c7271fb-353740b7/relevance/1