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FROM BIM TO DIGITAL TWINS: A SYSTEMATIC REVIEW OF THE EVOLUTION OF INTELLIGENT BUILDING REPRESENTATIONS IN THE AEC-FM INDUSTRY

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SUMMARY: *The widespread adoption of Building Information Modeling (BIM) and the recent emergence of Internet of Things (IoT) applications offer several new insights and decision-making capabilities throughout the life cycle of the built environment. In recent years, the ability of real-time connectivity to online sensors deployed in an environment has led to the emergence of the concept of the Digital Twin of the built environment. Digital Twins aim to achieve synchronization of the real world with a virtual platform for seamless management and control of the construction process, facility management, environment monitoring, and other life cycle processes in the built environment. However, research in Digital Twins for the built environment is still in its nascent stages and there is a need to understand the advances in the underlying enabling technologies and establish a convergent context for ongoing and future research. This paper conducted a systematic review to identify the development of the emerging technologies facilitating the evolution of BIM to Digital Twins in built environment applications. A total of 100 related papers including 23 review papers were selected and reviewed. In order to systematically classify the reviewed studies, the authors developed a five-level ladder categorization system based on the building life cycle to reflect the current state-of-the-art in Digital Twin applications. In each level of this taxonomy, applications were further categorized based on their research domains (e.g., construction process, building energy performance, indoor environment monitoring). In addition, the current state-of-art in technologies enabling Digital Twins was also summarized from the reviewed literature. It was found that most of the prior studies conducted thus far have not fully exploited or realized the envisioned concept of the Digital Twin, and thus classify under the earlier ladder categories. Based on the analysis of the reviewed work and the trends in ongoing research, the authors propose a concept of an advanced Digital Twin for building management as a baseline for further studies.*

KEYWORDS: *Built Environment; Building Information Modeling (BIM); Digital Twin; Internet of Things (IoT); Smart Buildings; Smart City.*

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1. INTRODUCTION

The lifecycle of a building primarily consists of the design, construction, operation, maintenance, and end of life stages where each stage can be divided into superimposed information layers that require efficient information exchange strategies for interoperability across all lifecycle stages (Vanlande et al. 2008). For example, information regarding design details needs to be exchanged between different engineering team members during the design stage, and different stakeholders need to communicate design and construction progress with each other during the construction phase (Hooper and Ekholm 2010). In addition, the building operation and facility management teams need to obtain feedback from the building facilities and occupants during operation (Das et al. 2015, Tang et al. 2020). A significant effort must therefore be invested to achieve efficient information update and exchange throughout a building's life cycle.

Starting from Computer-aided Design (CAD), tools for building design and management have evolved for decades. The term "Building Information Model" was first proposed in the early 90s (van Nederveen and Tolman 1992), which was later termed "Building Information Modeling (BIM)" and has attracted much attention and become widespread in the past decades (Li et al. 2017). As a 3D digital representation of buildings, a BIM model contains both geometric and semantic information of the building elements (Eastman et al. 2011).. Due to the sharable and consistent database, BIM makes the seamless collaboration between AEC (architecture, engineering, and construction) professionals possible and thus has been widely applied in building life cycle management, including the design stage (Oh et al. 2011, Afsari et al. 2019), construction process (Azhar et al. 2008, Singh et al. 2018, Deng et al. 2019, Deng et al. 2021) as well as operating phases (Bahar et al. 2013, Soust-Verdaguer et al. 2017).

For example, detailed geometric information associated with appropriate simulations (e.g., energy simulation and thermal environment simulation) can help with the design of the building and its systems (Sanguinetti et al. 2009, Abanda and Byers 2016, Gan et al. 2018, Tagliabue et al. 2018, Gan et al. 2019). BIM-based 4D simulations with detailed material and cost information can similarly provide support to the construction process of building projects (Yun et al. 2014, Lee and Kim 2017).In addition, with the help of 3D visualization and details of building elements provided by BIM, building management plans can be optimized by the building manager so as to help with the management of building equipment and the indoor environment (Cheng et al. 2016, Chen et al. 2018).

However, BIM itself can generally only provide static data of the built environment and cannot update real-time information in the models automatically without additional data sources (Tang et al. 2019). With the advent of Internet of Things (IoT), which is defined as the interconnection of sensing devices that are able to provide information exchange across different platforms (Gubbi et al. 2013), the integration of real-time sensing data and the static information provided by BIM models became possible (Tang et al. 2019).With the help of smart devices, visualization and analysis of real-time environmental data become available in BIM models, and automated update of BIM models based on real-time building status was achieved. For example, appropriate integration of BIM and IoT technologies can help with the real-time monitoring of the construction process and building indoor environment status (Lee et al. 2016, Dave et al. 2018, Li et al. 2018, Natephraa and Motamedib 2019). The basis of the integration of BIM and IoT has led to the emergence of the Digital Twin (Lu et al. 2020, Tagliabue et al. 2021).

The concept of the Digital Twin originated from the aerospace field (Shafto et al. 2010), and then expanded to industrial manufacturing (Negri et al. 2017, Kritzinger et al. 2018, Zhuang et al. 2018, Tchana et al. 2019, Zhang et al. 2019), has attracted increasing attention in the built environment domain in recent years. Existing studies have adopted BIM and IoT technologies for many aspects such as designing a building, monitoring, and management of construction processes, building facilities, and indoor environment management (Machado et al. 2018, Shahinmoghadam and Motamedi 2019, Tang et al. 2019). However, Digital Twins in the built environment are still in nascent stages and a systematic review of the evolution from BIM to Digital Twins and the current state-of-art technologies are necessary to establish a future research agenda.

This study provides an overall understanding of the development of technologies that have enabled Digital Twins in the built environment by reviewing and analyzing previous related literature. A total of 123 papers from a wide group of journals and conference proceedings were reviewed to provide a comprehensive understanding of the existing studies on the applications of BIM, IoT, and Digital Twins in the built environment. To enhance the understanding of related terms, a five-level ladder taxonomy is proposed to classify existing studies. In addition, based on the research gaps in prior studies, this paper also proposes the conceptual framework for an ideal Digital

Twin of the built environment as a reference for future research.

The remainder of this paper is structured as follows: Section 2 describes the methodology adopted for searching and categorizing the reviewed papers; Section 3 categorizes them according to the developed ladder taxonomy as well as research domains within each level; Section 4 summarizes the current state-of-art technologies and methods for achieving Digital Twins in the built environment; In Section 5, the authors describe the requirements and expected features of an ideal Digital Twin with an example for indoor environment control as a reference for future studies. Section 6 identifies the future outlook and presents the conclusion.

2. RESEARCH METHODOLOGY

2.1. Methodology of Review

The research began with a systematic literature review (Pawson et al. 2005) to locate and select relevant articles published in bibliographic databases. Three research questions were posed to facilitate the understanding of previous studies that supported the idea of Digital Twins.

Q1: How did Digital Twins evolve from BIM?

Q2: What are the built environment areas that concern Digital Twins?

Q3: What are the capabilities of current state-of-the-art Digital Twins?

To answer these research questions, the authors pursued the following steps. The first step was to collect relevant information regarding the related studies. The Google Scholar, Scopus, and ScienceDirect tools were used as the search engines to collect the articles of possible relevance, and the timeframe was set to be post-2010, as it was approximately the period that BIM was already widely adopted (Pezeshki and Ivari 2018, Gao and Pishdad-Bozorgi 2019). The keywords used in the search engine included “BIM”, “IoT”, and “Digital Twin” associated with “building”. These settings ensured that all relevant studies were identified, including both journal papers, conference papers, books, and theses.

The next step was to filter selected articles qualitatively for further analysis. The filtering process was conducted manually to select the target documents. Firstly, only English documents published in journal papers and conference proceedings were selected, with no specific limitation set for the type of journals or conferences. For example, journals such as Automation in Construction, Energy and Buildings, and Building Simulation were included, and conference proceedings such as from the International Association for Automation and Robotics in Construction (ISARC) and International Building Performance Simulation Association (IBPSA) were also selected. Secondly, due to the large number of BIM-related studies present in recent literature, instead of seeking original technical articles, review papers summarizing purely BIM applications (i.e., without being integrated with simulations or sensors) were selected to highlight state-of-the-art BIM-related studies. Thirdly, papers regarding supporting techniques (i.e., information transfer techniques) appurtenant to Digital Twins were not included. Finally, since real-time data visualization plays an important role in the development of Digital Twins (Schrotter et al. 2020), the identified articles without appropriate visualization platforms were excluded in this study. With this manual filtering, 123 articles were finally selected from the preliminary search.

2.2. Literature Analysis

Through the review of the relevant studies, 23 BIM review papers and 100 original papers were identified. In order to answer the first (Q1) and third (Q3) research questions, a corresponding classification system of relevant studies was needed. Therefore, this paper developed a five-level ladder taxonomy to reflect the evolution from BIM to Digital Twins, as shown in Figure 1. The five levels include Level 1 – BIM, Level 2 – BIM-supported simulations, Level 3 – BIM integrated with IoT, Level 4 – BIM integrated with artificial intelligence (AI) techniques for predictions, and Level 5 – ideal Digital Twins. To answer the second question (Q2), each level of the ladder taxonomy was divided into different sub-categories focusing on different research areas. The sub-categories were determined based on the building life cycle and the number of relevant papers that would comprise them.

For example, based on the building life cycle, studies in each level could be allocated into the design stage, construction phase, operation phase, and demolition phase (Sharma et al. 2011). Nevertheless, if a specific sub-category contained many papers, it could be further divided into specific research areas. For example, the building operation phase contains different research topics such as energy performance evaluation (Lee et al. 2016, Dave et al. 2018) and indoor environment monitoring (Nakama et al. 2015, Pasini et al. 2016, Kim et al. 2018). Table 1 summarizes the papers included in each level in this study. There are 23 review papers identified for BIM applications, 40 for BIM-supported simulations, 46 for BIM integrated with sensors for real-time monitoring, and 9 for BIM integrated with AI for predictions. However, the results revealed that no study has reached the anticipated Level 5 of the ladder taxonomy. Therefore, 6 studies that propose relevant concepts of the ideal Digital Twins were summarized. The systematic review of the previous studies thus provided the fundamental understanding for establishing the characteristics of an ideal Digital Twin of the built environment. The descriptions of studies at different levels in the proposed ladder taxonomy diagram are discussed in detail in the following sections.

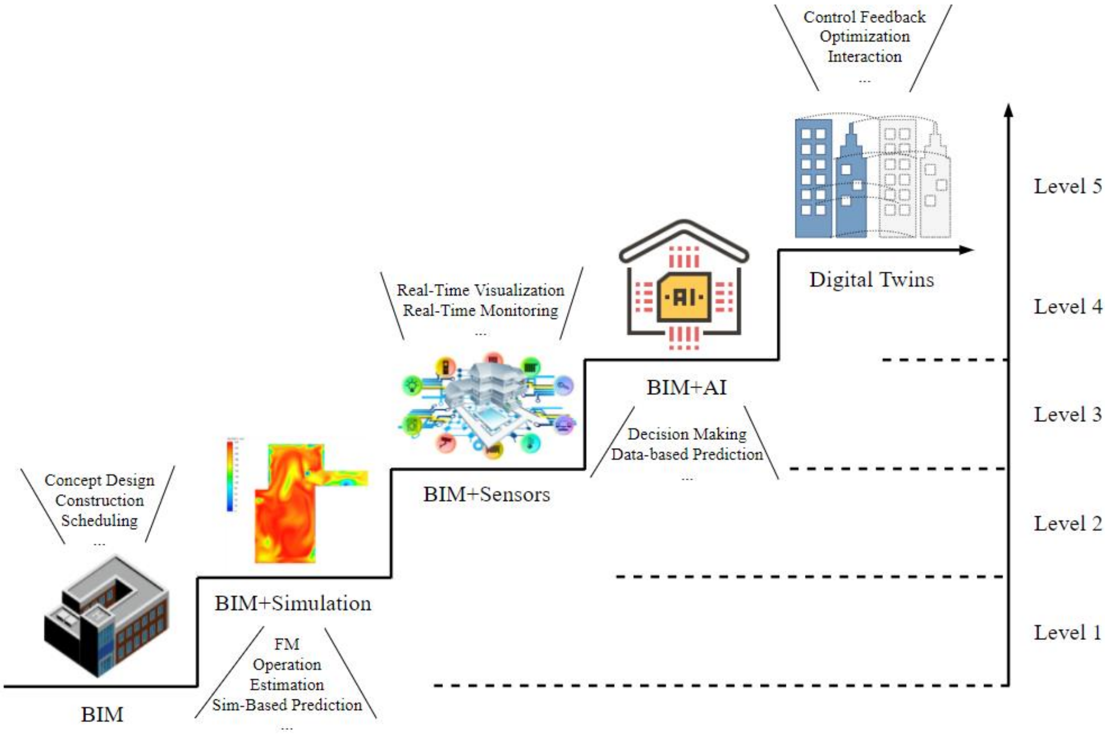


FIG. 1: Evolution of BIM to Digital Twins in the Built Environment

Table 1: Summary of the selected papers

Level	Number Papers
Level 1 (BIM Review)	23
Level 2 (BIM-supported Simulation)	40
Level 3 (BIM integrated with Sensors)	45
Level 4 (BIM integrated with AI)	9
Level 5 (Ideal Digital Twins Concept)	6
Total	123

3. PREVIOUS STUDIES REPRESENTING EVOLUTION OF BIM TO DIGITAL TWINS

3.1 Level 1: Applications of BIM Techniques

Studies in Level 1 use BIM as a static 3D visualization tool to provide required information to help with traditional ways of building envelope design, drawing modification, construction scheduling, cost estimation, and other functions. The application of BIM in this level aims to provide a better information sharing strategy between different stakeholders across the building life cycle. Instead of reviewing all the original papers, review papers concerning original BIM implementation studies in the past decade were reviewed in this section. The review papers were summarized according to the phases of building projects. For example, several review papers generally analyzed the value of BIM in building projects across various aspects (Volk et al. 2014, Zou et al. 2017, Liu et al. 2019), and others reviewed BIM applications in different phases of building projects including building design (Wong and Fan 2013, Soust-Verdaguer et al. 2017, Chang and Hsieh 2020), construction (Oraee et al. 2017, Santos et al. 2019, Wang and Meng 2019), and operation phases (Soust-Verdaguer et al. 2017, Dixit et al. 2019). Table 2 shows an overview of the summarized review papers with different foci.

Table 2: Categorization of Review Papers in Level 1 by Category

Category	**Related Articles**
General BIM Application Analysis	Volk et al. 2014, Chong et al. 2017, Zhao 2017, Zou et al. 2017, Pezeshki and Ivari 2018, Liu et al. 2019, Wang et al. 2019, Liu et al. 2017, López et al. 2018
Building Design Phase	Wong and Fan 2013, Soust-Verdaguer et al. 2017, Chang and Hsieh 2020
Building Construction Phase	Doumbouya et al. 2016, Eleftheriadis et al. 2017, Oraee et al. 2017, Santos et al. 2019, Wang and Meng 2019
Building Operation Phase	Wong and Zhou 2015, Lu et al. 2017, Ansah et al. 2019, Dixit et al. 2019, Gao and Pishdad-Bozorgi 2019, Kelly et al. 2013

3.1.1 General BIM Application Analysis:

In order to obtain an overview of BIM applications in different fields, several papers have conducted reviews of major existing BIM-related studies. Pezeshki and Ivari (2018), Liu et al. (2019) conducted a brief review on global BIM research in the AEC industry based on the researchers, research institutes, regions, and subject categories, which provided an overview of the current progress and future outlook of BIM applications in different research fields. Zhao (2017) had attempted to map the global research on BIM, based on the citations and frequently used keywords. For example, it was found that "visualization" and "industry foundation classes (IFC)" received burst citations and popular topics include mobile and cloud computing, laser scanning, augmented reality, ontology, code checking, safety rules, semantic web technology, and automated generation.

In addition, some research gaps or challenges were found in some review papers. For example, a mixed review of BIM development for sustainability was conducted by Chong et al. (2017) and the results revealed that little work was conducted regarding BIM application in refurbishment and demolition. Besides, Volk et al. (2014) presented a review of BIM implementation and research in existing building projects and found corresponding challenges such as high conversion effort in filling out semantic information, updating of BIM information, and handling of uncertainties.

Moreover, a few studies have investigated other BIM-related fields in general ways. For example, Zou et al. (2017) presented a comprehensive review of BIM and BIM-related technologies in risk management across the whole building life cycle, where the results showed that BIM could not only serve as a systematic risk management tool but also could be considered as a platform for further risk analysis using other BIM-based tools. It also provided some comments on overcoming the existing technical limitations in real environments, including (1) making the system multi-disciplinary, (2) investigating methods and processes regarding the implementations, (3) involving new technologies, and (4) supporting the development process. Liu et al. (2017), Wang et al. (2019) presented a review on BIM-GIS integration in the field of sustainable built environments, which aimed to analyze the status quo of their application in four aspects: data integration technologies, life cycle in AEC projects, building energy management, and urban governance. López et al. (2018), explored the effectiveness and usefulness of BIM implementations in cultural heritage, which demonstrated that Heritage BIM (H-BIM) was useful by facilitating the interdisciplinary exchange of both geometric and semantic information in the architectural heritage field.

3.1.2 Building Design Phase:

Chang and Hsieh (2020) conducted a comprehensive review of BIM research to provide insights on trends and future potential of green buildings. The reviewed paper mainly focused on the design analysis of the buildings which found that energy and thermal analyses, and cost-benefit analyses were the most studied, while ventilation, acoustic, and water efficiency analyses were not being investigated a lot. After conducting a literature review and interviews, Wong and Fan (2013) confirmed the value of BIM in sustainable design and integrated project delivery (IPD). Soust-Verdaguer et al. (2017) reviewed studies on BIM implementations in Life Cycle Assessment (LCA), which mostly focused on CO_2 emission during design stages. The results showed the capability of BIM in estimating environmental and energy consumption impacts using templates and plug-ins for BIM software and automated integration of different data**.**

3.1.3 Building Construction Phase:

Several researchers have summarized the existing studies on BIM applications in the building construction phase as a map for future studies. For example, in order to understand the development of BIM in construction in a historical way, Wang and Meng (2019) identified papers of IT-based and BIM-supported knowledge in construction stages, which highlighted the current status and future directions based on the transformation from IT-based to BIM-supported workflows. In addition, Oraee et al. (2017) conducted a bibliometric analysis of studies regarding BIM-based construction networks and found that BIM projects have mainly focused on technologies and less on various aspects of management. Doumbouya et al. (2016) reviewed related articles regarding BIM adoption in construction projects, which concluded that BIM could benefit the construction process in aspects of constructability including improvement of information ability, and reduction of design errors. In addition, the improved management efficiency of the project could lead to the reduction of construction cost and time and improvement of energy efficiency.

Santos et al. (2019) reviewed the studies on BIM in sustainable construction and found that BIM was increasingly being used as a reliable approach for sustainable construction, which divided the related studies into three environmental, economic, and social dimensions. In addition, after evaluating the existing studies, Eleftheriadis et al. (2017) explored the capabilities of BIM in the energy efficiency of building structural systems, which argued the necessity of BIM in future sustainable decision-making of building structures so as to balance the energy efficiency and engineering performance indexes.

3.1.4 Building Operation Phase:

Due to the advanced data storage capability and vivid representation of building information, BIM has been considered to be very useful during building operation stages. Therefore, many studies have tried to review the status quo of BIM applications in building operation and maintenance such as life cycle assessment and facility management. For example, Lu et al. (2017) reviewed the studies regarding the nexus between BIM and green buildings and systematically illustrated them with a “Green BIM Triangle” taxonomy, which provided important guidance for aligning BIM development with green buildings. Similarly, Wong and Zhou (2015), Ansah et al. (2019) also provided a thought-provoking insight into existing green BIM literature as a reference for future research. The research found that more studies were related to the design and construction stages, while few were in the aspects of building maintenance, retrofitting, and demolition stages. Dixit et al. (2019), Gao and Pishdad-Bozorgi (2019) evaluated and summarized recent studies regarding BIM for facility operation and maintenance (O&M), which showed that BIM for O&M was still in its early stage and there were some challenges that need to be addressed. Examples include data interoperability, O&M principles for BIM implementation, and justification of the financial value of BIM-O&M applications in a building’s life cycle. Similarly, Kelly et al. (2013) conducted investigated the values of BIM for FM and concluded that it could improve the efficiency of the data exchange process. Furthermore, a survey of FM professionals revealed that the most important issue is the lack of FM involvement when the BIM evolves (Dixit et al. 2019).

The above reviewed studies indicate that BIM can provide both geometric and semantic information of building projects, which can enhance the information exchange between different stakeholders, thereby improving the efficiency in building design, construction, and building operation phases. However, BIM models can only provide static raw information, while sometimes it is necessary or useful to evaluate projects in different aspects such as the integration of building design and construction schedules, which lead to the next level of BIM implementation.

3.2 Level 2: BIM-Supported Simulations

In addition to relying solely on static BIM models for traditional conceptual design and facility management based on 3D walkthroughs, this level starts to incorporate different analyses and simulations with BIM models. Rather than being used as a visualization tool, BIM models in this level are used as data sources for conducting further analysis of construction processes or building performance. Therefore, rather than treating BIM as a static 3D visualization tool, studies in this section further integrate the project information stored in BIM with different data analysis and simulations. The related papers were summarized according to their specific implementations in building projects. They were divided into construction process simulation (Song et al. 2012, Yun et al. 2014, Habibi 2017), energy performance evaluation (Kim and Woo 2011, Bahar et al. 2013, Ryu and Park 2016), thermal environment assessment (Laine et al. 2007, Gan et al. 2019, Lee et al. 2019), and others such as lighting (Kota et al. 2014) and acoustic (Wu and Clayton 2013) simulations. Table 3 shows an overview of the studies with different research domains.

Table 3: Categorization of Reviewed Papers in Level 2 by Research Domains

Research Domains	**Related Articles**
Construction Process Simulations	Song et al. 2012, Liu et al. 2015, Habibi 2017, Zhang et al. 2011, Yun et al. 2014, Jeong et al. 2016, Zhang et al. 2016, Lee and Kim 2017
Energy Performance Evaluation	Sanguinetti et al. 2009, Cho et al. 2010, Corry et al. 2011, Kim and Woo 2011, Moon et al. 2011, Bahar et al. 2013, Jung et al. 2013, Maile et al. 2013, Asl et al. 2014, Gupta et al. 2014, Katranuschkov et al. 2014, Ham and Golparvar-Fard 2015, Kim et al. 2015, Abanda and Byers 2016, Ryu and Park 2016, Tagliabue et al. 2018, Lee et al. 2019
Thermal Environment Evaluation	Laine et al. 2007, Welle et al. 2011, Pazhoohesh et al. 2015, Gan et al. 2019, Lee et al. 2019, Ma et al. 2019, Shahzad et al. 2019
Other BIM Supported Simulations	Lee and Song 2010, Kovacic et al. 2013, Wu and Clayton 2013, Yan et al. 2013, Cheng and Das 2014, Kota et al. 2014, Gan et al. 2018, Park et al. 2018

3.2.1 Construction Process Simulations:

In the early stage of the building construction, BIM-supported simulations were widely applied to help with the scheduling and optimization of the construction process. To that end, different simulation strategies were applied to prove the capability of BIM in improving construction processes and enabling explorations of alternative designs and operations (Habibi 2017). For example, Song et al. (2012) proposed an optimization and simulation system for better management of construction planning and scheduling using BIM, which also provided a dynamic visualization of the simulated construction process.

Similarly, to improve productivity as well as balancing the production line, Liu et al. (2015) developed an automated construction planning approach, and Yun et al. (2014) proposed a BIM-based construction simulation system and compared it with the existing commercial system by a newly developed methodology. The results confirmed the speed superiority and higher efficiency of the prototype. Jeong et al. (2016), on the other hand, presented a BIM-integrated framework to simulate the dynamic productivity plan and calculate the per-hour rate of production of the project, which established a more reliable construction plan compared to traditional construction planning approaches.

In order to show the improvement in a more explicit way, a quantitative way for the assessment of building constructability was proposed to help with the analysis and the improvement of building design and construction by Zhang et al. (2016). In addition, as modular construction is becoming increasingly popular, BIM-based 4D simulation was also investigated by Lee and Kim (2017), aiming to improve the management efficiency of modular construction projects, which significantly reduced the time in providing proven table reviews as well as training through providing the visualization information. To improve the safety of the construction process, Zhang et al. (2011) developed an automated BIM-based safety code checking tool, which could potentially minimize the potential errors and waste in safety planning on construction sites.

3.2.2 Energy Performance Evaluation:

In addition to the construction stage, BIM-supported simulations for building energy performance evaluation have also been an active research area, because BIM can provide not only the geometry for the simulation but also some required information such as building materials, which significantly improves the simulation efficiency and accuracy. Bahar et al. (2013) described potential opportunities (e.g., time-savings) as well as challenges (e.g., interoperability) for applying BIM-based energy simulation tools in building performance optimization.

In order to verify the capability of BIM-based energy simulation, Kim and Woo (2011) analyzed the difference in energy simulation results between BIM-based methods and the detailed simulation method (DOE 2.2 simulation engine). The results indicated that although more specific information on the HVAC system needs to be engaged in BIM-based simulation, it was generally faster and more efficient. Similarly, Ryu and Park (2016) conducted a BIM-based energy simulation based on LEED certification, which revealed that a considerable amount of time savings with faster and easier error solving could be achieved with the help of BIM.

BIM-supported simulations could provide a better future view of the buildings so as to provide useful insights into building design. For example, Sanguinetti et al. (2009) applied BIM in decision making during concept design stages by comparing different scenarios, and showed the relationship between energy consumption and building design parameters. Similar methods were also applied to analyze the energy performance improvement of different categories of buildings such as schools (Tagliabue et al. 2018). Similarly, Abanda and Byers (2016) evaluated the impact of orientation on small-scale building energy consumption and concluded that a well-oriented building can help with a considerable amount of energy-saving throughout the building's entire life cycle.

BIM models can also be integrated with different algorithms for predictions. For example, to investigate the occupant-based energy consumption as a function of user activities in an indoor environment, Lee et al. (2019) developed an artificial neural network (ANN) based approach, and found that more energy was consumed by females than males did, and unemployed, low-income and less educated individuals also tend to use more energy. Jung et al. (2013) applied a genetic algorithm (GA)-based on the optimization of building energy performance.

Due to the good compatibility of the IFC format, BIM was also applied to support sustainable designs of the building, such as renewable energy simulation (Gupta et al. 2014) and sustainable fixtures (Cho et al. 2010). In terms of buildings with complex kinetic façades, Kim et al. (2015) proposed a new approach through dynamic generative design in BIM platforms to conduct building energy performance. Similarly, Asl et al. (2014) proposed a new BIM-based parametric design system to integrate the cloud-based building energy and daylight analysis that aimed to optimize the building energy performance by the developed algorithm.

However, due to potential data loss and incompatibility of BIM models and some simulation platforms, some challenges were also raised and several studies were conducted to solve them, such as Katranuschkov et al. (2014), who developed an energy-enhanced BIM framework to bind distributed model data and enable the interoperability of different energy monitoring and analysis through an Integrated Virtual Energy Lab Platform. Moon et al. (2011) also conducted a study with several case studies to evaluate the interoperability between BIM models and building performance analysis platforms such as eQuest, EnergyPlus, and IES. Maile et al. (2013) developed data requirements for building performance simulation and described several case studies with problems where models did not comply with required data quality standards.

On the other hand, to eliminate the simulation errors caused by deviations of building parameters, Ham and Golparvar-Fard (2015) developed a method to automatically detect the as-is building thermal properties using the thermographic sensing technique. Furthermore, Corry et al. (2011) proposed a conceptual framework that could be used as metrics for building performance assessment in a standardized fashion.

3.2.3 Thermal Environment Evaluation:

The application of BIM has a lot of benefits in thermal performance management, including more efficient data exchange, more dynamic simulation, and easier verification, by integrating with Computational Fluid Dynamic

(CFD) simulations (Laine et al. 2007). To increase the reliability of the BIM-based building performance analysis with more accurate thermal property information, Lee et al. (2019) also conducted a preliminary study that applied BIM-based simulation tool and CFD for improvement of the HVAC system considering thermal comfort level. A novel BIM-based framework was also developed for analyzing the effect of natural ventilation on building energy efficiency and indoor thermal comfort, which integrated the effects of external wind pressure in achieving a more precise CFD simulation for thermal comfort Gan et al. (2019).

Similarly, with the help of BIM and CFD simulation, Pazhoohesh et al. (2015) simulated different scenarios of HVAC operating conditions to investigate the corresponding effect of thermal comfort as well as the energy-saving amount. Based on the BIM platform, machine learning (ML) algorithms were integrated into indoor thermal comfort prediction. For example, Ma et al. (2019) developed an artificial neural network (ANN) model to predict personal thermal comfort and evaluate the energy-efficient design of indoor spaces, which helped increase the accuracy of thermal comfort prediction associated with energy-saving strategies.

Shahzad et al. (2019), however, designed a Visual Thermal Landscaping (VTL) model to represent the thermal scenarios of the indoor environment in a systematical way, through which they were able to conclude different patterns of thermal comfort preference as well as provide specific insights regarding the design or arrangement of seats in buildings. Meanwhile, Welle et al. (2011) described a methodology called "ThermalOpt" to conduct multidisciplinary thermal simulations in an automatic way for design optimization with the help of BIM techniques, aiming to facilitate the building design process as well as increasing its accuracy and consistency.

3.2.4 Other BIM Supported Simulations:

In addition to major research domains related to construction, energy performance, and thermal environment, some other areas such as embodied carbon, lighting, and acoustics have also been studied occasionally, as BIM-based multi-disciplinary planning process simulation was conducted across the fields of architecture, structure, and building physics (Kovacic et al. 2013). For example, Cheng and Das (2014) developed a BIM-based web server framework that could be utilized to perform green building design functions such as code checking, energy simulation as well as design and updating of BIM models.

The application of BIM in daylighting performance simulation and analysis was also conducted by Kota et al. (2014). Similarly, Yan et al. (2013) presented the development of system interfaces that integrated BIM with building energy modeling as well as daylighting simulation through a developed Application Programing Interface (API) in BIM authoring tools. Wu and Clayton (2013) developed a BIM-based framework for acoustic simulation for building indoor environment by extracting necessary data from Revit models and thereby driving the simulation, which could also be re-stimulated immediately by modifying the Revit files to achieve a real-time update of the simulation.

Lee and Song (2010) conducted CFD simulations for wind environment evaluation for pedestrians near building stocks with the help of BIM. Gan et al. (2018) proposed a holistic BIM framework for evaluating and design of high-rise buildings, in which the operational and embodied carbon emissions were integrated, and different scenarios of building envelopes were analyzed with the help of the framework. In regard to safety concerns, BIM associated with Virtual Reality (VR) was also used for the safety design of building environments by conducting simulations of human behaviors related to emergencies such as fire alarms (Park et al. 2018).

Although appropriate analysis and simulations based on static project information can improve the efficiency and quality of the building environment in earlier stages such as the design stage and construction stage, it has a limited impact on later phases of the building life cycle such as the operation stages. In addition, since the buildings may change with time, a more efficient way of tracking building status is required for an improved understanding of the building life cycle, which has led to studies in Level 3.

3.3 Level 3: Integration of BIM and IoT Techniques

Studies at this level start to connect digital building models with real-time sensing data for building environment monitoring and management. After incorporating different smart IoT sensors, real-time building environment data can be easily obtained and visualized in 3D digital models, which can be helpful for in-time decision-making or strategy changing during any phases of the building life cycle. Therefore, potential opportunities for enhancing BIM by utilizing IoT techniques were discussed and investigated significantly (Mahsa Pahlavikhah and Aghajani 2017) in the past decades. The related papers in this section were summarized in categories based on their specific implementations in building projects. The categories include monitoring of construction process (Liu and Deng 2017, Li et al. 2018), energy performance (Lee et al. 2016) (Dave et al. 2018), indoor environment (Nakama et al. 2015, Pasini et al. 2016, Kim et al. 2018), indoor thermal comfort (Chang et al. 2018, Pasini 2018), indoor hazards (Chen et al. 2018, Wehbe and Shahrour 2019), multi-building (Ruohomäki et al. 2018, Shipman and Gillott 2019), as well as the management of building space (Fang et al. 2016, Ha et al. 2018). Table 4 summarizes the overview of the studies in Level 3 with different research domains.

Table 4: Categorization of Reviewed Papers in Level 3 by Research Domains

Research Domains	**Related Articles**
Construction Process Monitoring	Liu and Deng 2017, Han and Ye 2018, Kassem et al. 2018, Li et al. 2018, Natephraa and Motamedib 2019
Energy Performance Management	Lee et al. 2016, Bottaccioli et al. 2017, Dave et al. 2018, Francisco et al. 2018, Machado et al. 2019, Rinaldi et al. 2019, Rafsanjani and Ghahramani 2020
Indoor Environment Monitoring	Marzouk and Abdelaty 2014, Nakama et al. 2015, Riaz et al. 2015, Tomasi et al. 2015, Pasini et al. 2016, Suprabhas and Dib 2017, Kang et al. 2018, Kim et al. 2018, Sava et al. 2018, Zhong et al. 2018, Atazadeh et al. 2019, Ignatov and Gade 2019, Rashid et al. 2019, Zhao et al. 2019
Indoor Thermal Comfort	Chang et al. 2018, Ioannou et al. 2018, Pasini 2018
Space Management	Fang et al. 2016, Chen et al. 2017, Teizer et al. 2017, Ferreira et al. 2018, Gong et al. 2018, Ha et al. 2018, Asadi et al. 2019, Chen et al. 2019, Mahmood et al. 2020
Hazards Monitoring	Cheung and Lin 2016, Chen et al. 2018, Eftekharirad et al. 2018, Huang et al. 2018, Wehbe and Shahrour 2019
Community Monitoring	Ruohomäki et al. 2018, Shipman and Gillott 2019

3.3.1 Construction Process Monitoring

Real-time monitoring has been increasingly applied in construction sites with the development of BIM and IoT technologies, as it can provide a dynamic update of the construction process and lead to the efficient management of the construction site. For example, Kassem et al. (2018) integrated BIM and IoT for the management of site equipment based on the interviews with experts for identifying the key challenges in the site equipment fleet. Han and Ye (2018) proposed a generic concept to integrate IoT and cloud-based BIM for the monitoring of precast components, the system made the information of prefabricated components traceable at any time.

In order to deal with the challenges of incomplete and inaccurate data exchange during on-site assembly services (OAS), Li et al. (2018) developed a BIM-based platform for real-time visualization of the on-site assembly of prefabricated construction processes. It applied radio frequency identification (RFID) technology to collect real-time data and virtual reality (VR) technologies for visualization, thus improving the efficiency and daily operations, collaboration, decision making, and supervision. Similarly, Natephraa and Motamedib (2019) achieved a live visualization of sensing data based on BIM and Augmented Reality (AR). In addition, Liu and Deng (2017) proposed a systematic method for integrating BIM and sensors for sustainable construction design.

3.3.2 Energy Performance Management

Real-time energy evaluation and management of a building is a key to achieve efficient and sustainable buildings. BIM and IoT applications in building energy performance management were thus widely investigated. Lee et al. (2016) carried out a study that relies on Autodesk Revit, web-browsers, and building automation systems to create a real-time visualization of building energy consumption that achieved 17% energy savings due to the easier information acquisition that led to improved control of lighting and air-conditioning systems. Similarly, by integrating BIM and IoT devices through open messaging standards (O-MI and O-DF) and IFC models, Dave et al. (2018) developed a web-based platform named Otaniemi3D to integrate IoT sensors with built environment data on a campus-scale, which provides information on energy consumption of facilities and occupant comfort, thus enhancing facility management efficiency due to better decision-making strategies.

Meanwhile, Bottaccioli et al. (2017) developed a cloud-based software architecture that integrates heterogeneous IoT and simulation results for building energy evaluation. Instead of using historical data, they obtained the real weather data from the nearest weather station, which drastically improved the accuracy of the simulation results. Francisco et al. (2018), developed a technique to represent measured energy consumption data in as-built BIM and showed its potential in driving the energy-saving behavior of occupants to provide better automatic transmission of sensor information to BIM platforms.

Rafsanjani and Ghahramani (2020) proposed a novel approach that incorporated IoT sensors using Wi-Fi to evaluate the energy behavior of individuals in the office, which can be applied to identify inefficient behavior of individuals and responding to it, thereby driving the energy-saving behavior. Similarly, Rinaldi et al. (2019) proposed an IoT framework to estimate the indoor conditions as well as occupancy rates, which provided hints for energy-saving strategy by further understanding the pattern of the indoor conditions. Machado et al. (2019) developed an interface layer that helps with the integration of BIM and IoT for real-time building energy performance monitoring. Visual Programing Language (VPL) scripts were developed to enable the dynamic exchange of information between BIM and IoT interfaces.

3.3.3 Indoor Environment Monitoring

Nakama et al. (2015), Pasini et al. (2016), Kim et al. (2018) defined frameworks that integrated IoT and BIM for the management of cognitive buildings. Kang et al. (2018) introduced a BIM and IoT-based monitoring framework and a prototype system for providing a comprehensive view of the status of buildings and indicated better performance of time-series database compared with traditional ones. BIM and IoT sensors have also been applied to monitor the public spaces. For example, Marzouk and Abdelaty (2014) integrated wireless sensor networks (WSN) with BIM to monitor temperature and humidity levels in subways. Suprabhas and Dib (2017) also developed an application that integrated WSN with BIM through construction operations building information exchange (COBIE), aiming for better facility management.

Zhong et al. (2018) presented an ontology-based framework for compliance checking and monitoring by collecting heterogeneous data using sensors and BIM techniques. A similar platform was also developed for sensing data visualization in BIM by (gnatov and Gade (2019). For multi-owned buildings, the use of BIM environment was also confirmed to be useful in communicating rights, restrictions, and responsibilities of the datasets collected by IoT devices (Atazadeh et al. 2019). Based on BIM and Unity3D, Zhao et al. (2019) developed a human-activity simulator named BIM_{3D}^{Sim}, which could be applied to evaluate activity-recognition methods for indoor environments.

BIM-IoT integration has also been considered as a key feature for smart buildings. For example, Sava et al. (2018) analyzed the way that digital technologies could be implemented to achieve smart buildings with the help of IoT, and Rashid et al. (2019) proposed an intuitive framework that integrated IoT and BIM to control the electric fixtures for a smart building, in which the indoor position and orientation of the users could be detected using ultra-wideband (UWB) -based indoor positioning system as well as inertial measurement units (IMUs).

Similar methods (UWB with BIM) were also applied to aid the wireless sensor networks (WSN) planning in buildings (Tomasi et al. 2015). Furthermore, in order to reduce health and safety hazards, Riaz et al. (2015) developed a prototype that collects real-time temperature and oxygen as the basis for decision-making for evacuation planning and reported the potential challenges encountered in the developed system.

3.3.4 Indoor Thermal Comfort

Real-time monitoring of the indoor environment could also be very helpful in predicting and visualizing real-time indoor thermal comfort with the help of BIM and IoT technologies. Chang et al. (2018) developed a framework using Dynamo to transform real-time sensing data from Arduino Microcontroller to Autodesk Revit, to achieve colorful visualization of indoor temperature and humidity as well as thermal comfort in BIM models, similar to the platform developed by Pasini (2018). However, Ioannou et al. (2018) evaluated the adaptive thermal comfort model by comparing the estimated thermal comfort values quantitatively and qualitatively using real-time indoor temperature, relative humidity, metabolic rate, and clothing, which indicated that the adaptive thermal comfort model would overestimate or underestimate the results.

3.3.5 Space Management

"BIM has been integrated with smart sensors for space management in the built environment (e.g., indoor asset localization). For example, a method was developed by utilizing image-based indoor localization with the help of BIM and cameras. The model applied a convolutional neural network (CNN) and achieved an accuracy of 91.61% for matching photographs (Ha et al. 2018). Similarly, Mahmood et al. (2020) proposed a computer-vision method for easier management of the indoor space, which could match the real room and the place in an as-built BIM model, thus localizing them in the model. Asadi et al. (2019) proposed an image-based technique for the construction site, which could achieve real-time mapping of the real site to corresponding BIM views, thus facilitating the communication of the construction process.

Apart from computer vision-based techniques, other techniques such as radio-frequency identification (RFID), Bluetooth Low Energy (BLE), radio signal strength index (RSSI), and Wi-Fi fingerprinting were also used to support BIM usage for real-time space management. For example, Fang et al. (2016) introduced a BIM and cloud-enabled RFID system to localize mobile construction resources. The system contained a BIM visualization system, RFID localization system, and cloud computing system, which could improve the accuracy and reliability of the construction process, and provided timely warnings of potential hazards for onsite workers. Teizer et al. (2017) proposed the concept for real-time tracking of environmental parameters and localization of workers in indoor environments. The design consists of BLE beacons, personal protective equipment (PPE), cloud-based BIM as well as IoT techniques. Similarly, based on BLE signals from beacons, Ferreira et al. (2018) and Gong et al. (2018) developed systems that could provide useful information about the movements and location of occupants inside a building through a smartphone and could guide them to the desired destinations. Chen et al. (2017) integrated BIM with RSSI-based localization techniques, which filtered 25.6% of the infeasible positions thus leading to higher accuracy. Moreover, Chen et al. (2019) developed a location-aware augmented reality (AR) framework for indoor facility management, which applied the K-nearest neighbor algorithm to help with the real-time localization based on Wi-Fi fingerprinting. Their results showed a time reduction of around 65% for the designed task.

3.3.6 Hazards Monitoring

Real-time monitoring could also make the built environment a safer place. For example, Wehbe and Shahrour (2019) briefly discussed the potential of BIM and IoT in identifying indoor hazards, including fire hazards, indoor air pollution, water and gas leaks, domestic accidents, and domestic appliance faults. For fire rescue, Chen et al. (2018) proposed a BIM-based visualization and warning system that could be used in fire rescue. A fire simulation of various conditions was able to be conducted and visualized before the fire rescue, and IoT technology allowed real-time situation monitoring. A similar study was also carried out by , Huang et al. (2018).

Meanwhile, Eftekharirad et al. (2018) developed an extended IFC model to enable BIM to serve as an improved technique for fire emergency management. Moreover, Cheung and Lin (2016) developed a BIM-WSN Safety Monitoring System for real-time monitoring of hazard gases in construction sites. Zigbee WSN sensor nodes were applied to collect hazard gas concentration reflected using color changes in BIM models, thereby enhancing efficiency and quality of safety management as well as decision making.

3.3.7 Multi-building Monitoring

In addition to an individual building, BIM-IoT integration is also a key to monitoring multiple buildings such as communities and cities. For example, an urban scale Digital Twin is under development by Ruohomäki et al. (2018), which integrates building automation systems and sensor points in cities based on CityGML, trying to achieve a platform for co-design and development. In addition, to facilitate the adoption of community energy schemes, Shipman and Gillott (2019) developed a framework that integrates different sensors and smart meters of building systems to provide data to a cloud database, which provides information regarding the possible actions that could be used to reduce energy consumptions.

Based on the real-time sensing data, additional studies have done a further analysis and integrated real-time prediction as part of the developed technical approaches. These studies are summarized in the next section and classified as Level 4 applications.

3.4 Level 4: BIM and IoT integration Associated with Real-Time Predictions

Studies in this level have further enhanced the building environment monitoring and management by incorporating algorithms for real-time predictions based on models developed using data collected from smart sensors. With appropriate decision-making strategies based on real-time prediction, more accurate and reliable strategies can be obtained automatically or semi-automatically by the building manager so as to achieve more efficient building operation and facility. The reviewed papers that primarily focused on the construction and operation phases of building projects were summarized in Table 5.

Table 5: Categorization of Reviewed Papers in Level 4 by Research Domains

Research Domains	Related Articles
Building Construction Phase	Pour Rahimian et al. 2020, Qureshi et al. 2020
Building Operation Phase	Liu et al. 2014, Chen et al. 2019, Escandón et al. 2019, Lydon et al. 2019, Austin et al. 2020, Cheng et al. 2020, Gao et al. 2020

Integration of BIM, IoT, and the real-time prediction was investigated to help with the construction process of the buildings. Pour Rahimian et al. (2020) proposed a framework to allow automated simulation of construction projects. Unity game engine was utilized to integrate the data from BIM and real-world images, through the ML algorithms, the system could update the 3D virtual view of the construction site, thus providing an advanced decision-making tool for different stockholders of the project. Similarly, based on ML techniques, a theoretical framework that could detect the progress of the project was proposed by Qureshi et al. (2020).

Apart from the construction phase, Digital Twins with real-time predictions are also widely investigated in building operation phases. For example, Lydon et al. (2019) proposed a simulation and monitoring method to help with both the design and operation stages of a roof by integrating sensors and CFD simulations, which is expected to reduce the planning resources as well as achieve a better life cycle monitoring and control of the roof. In addition, Escandón et al. (2019) developed an ANN-based model to speed up the thermal comfort prediction, where the surrogate model was fed by simulation results and achieved 98% saving of computational time. In order to have a better visualization of indoor thermal comfort, Liu et al. (2014) similarly developed a visualization platform to collect data from IoT sensors and present them using a developed interface in Revit, which also estimated the thermal comfort of the occupants in that environment. Chen et al. (2019), Cheng et al. (2020) proposed a data-driven framework for the FM of the indoor system. The developed approach applied ANN and support vector machine (SVM) to predict the future conditions of the MEP components based on the condition monitoring of the equipment, thus help with the scheduling of the maintenance tasks. Gao et al. (2020) developed a framework to forecast the life-cycle-cost (LCC) of the building facilities. The study concluded the feasibility of using machine learning techniques to predict the LCC of facilities based on the data from current systems. Austin et al. (2020) discussed approaches and challenges of the smart city Digital Twins, which proposed to integrated ML to analyze the energy usage of the buildings, a case study was exercised on buildings located in Chicago Metropolitan Area.

3.5 Conceptual Framework of Ideal Digital Twin in the Built Environment

Although often unaccompanied by real-world case studies, several research studies have proposed conceptual Digital Twin frameworks or prototypes in built environment management. For example, driven by the UK's needs for a digital framework for data on infrastructure, Lu et al. (2019), Lu et al. (2020) proposed a systematical architecture on how to develop a dynamic Digital Twin that can integrate heterogeneous data sources with a case study in the West Cambridge Campus. The architecture contains four basic layers, which from the bottom to top are the data acquisition layer, transmission layer, data model integration layer, and application layer. To further support their Digital Twin architecture, they also proposed a novel data structure based on industry foundation classes (Lu et al. 2020).

The data acquisition layer describes different possible raw data from various data sources, followed by information transmission and integration using technologies such as 5G and LP-WAN. Digital modeling and complementary data matching are carried out based on technologies such as BIM to integrate different algorithms and simulations. Alonso et al. (2019) pursued a four-year EU-funded Digital Twin project named SPHERE (Service Platform to Host and SharE Residential data), aiming to provide an integrated ICT (Information and Communication) platform for better design, construction, and performance evaluation of residential buildings. In addition, Mohammadi and Taylor (2019) proposed a game-theoretic approach that aimed to enable the analysis of city-scale Digital Twin. The concept they proposed intends to integrate human, infrastructure, and technology in decision making.

Similarly, Schrotter et al. (2020) described a Digital Twin for the City of Zurich and proposed several future actions to make the Digital Twin a higher level.

3.6 Summary of Literature Associated with Proposed Ladder Categories

It can be observed that a large portion of the previous studies was classified as Level 2, meaning that many of the previous real-world applications of "Digital Twins" starting from BIM-supported simulations for tasks such as 4D construction process simulations and building energy performance evaluations have been shown to help with the evaluation of the building life cycle and achieve a more efficient and environmentally friendly building.

Similarly, studies in Level 3 also play significant roles in the reviewed papers, indicating that increasing research studies have started to work on real-time built environment management by integrating IoT technologies with BIM, which demonstrate further improvement in efficiency and reliability of the built environment control and management as the real-time data can provide a more precise on-going status of the buildings.

It was observed that although several recent studies start with the intent of applying BIM for higher-level applications, they generally limit themselves to staying within the original applications of BIM, as most of them strongly classify in Level 2 and Level 3 categories. In addition, fewer studies were found to classify under higher-level applications (Level 4 and Level 5), meaning that those applications and implementations are still emerging research areas that are likely to attract increasing attention in the upcoming future. Therefore, additional research is needed to achieve an ideal Digital Twin that contains not only real-time monitoring and prediction capabilities within the built environment, but also enables automated feedback control for adjustment of building parameters when necessary. This framework is further described in detail in Section 5.

4. CURRENT STATE-OF-THE-ART AND KNOWLEDGE GAPS IN DIGITAL TWIN TECHNIQUES

Based on the analysis of the reviewed literature, it is observed that the current level of advancement in enabling technologies has facilitated the following state-of-the-art applications and implementations of Digital Twins in the built environment: Real-Time Monitoring; Performance Prediction; and Strategic Improvement.

4.1 Real-Time Monitoring

In terms of real-time built environment monitoring, the current state-of-art studies and resulting implementations can collect data from the building indoor environment or construction site through IoT technologies such as Wi-Fi, WSN, 5G, LP-WAN, and surveillance cameras. The real-time sensing data can be adequately displayed on neutral platforms such as computer terminals or cloud-based interfaces, thus achieving synchronous visualization of the built environment. The real-time visualization of building status can represent an information-rich view of either the construction process or the indoor environment status to the building or project managers, leading to more efficient management.

4.2 Performance Prediction

For the prediction of the building status, the current state-of-art technologies can mainly be categorized as simulations (e.g., construction 4D simulation, energy simulation, lighting simulation, thermal comfort prediction) and ML techniques (e.g., ANN, SVM). Simulations are mainly applied in relation to building performance (e.g., energy consumption, lighting, acoustic, emergencies) or the construction process. On the other hand, ML techniques are intensively implemented in the prediction of the status of specific target parameters such as occupants' comfort as it requires ground truth data from experiments to train the models.

4.3 Decision-Making System

In terms of decision-making, most of the relevant studies still involve human in the control loop to make the final decisions based on the collected real-time data (e.g., construction progress, indoor temperature, humidity) or gleaned insights from the predicted results (e.g., energy consumption, thermal comfort). Various scenarios of strategies (e.g., look-ahead simulations) are also considered to allow decision-makers to decide on the best possible control options based on the comparison results. Overall, the current Digital Twins play the role of integrating the real-time information with corresponding automated processes, which helps the decision-making system in the management of the built environment.

4.4 Gaps in Current Knowledge

Although several research studies have contributed to the incremental advancement of Digital Twins and enabling technologies for the built environment, there still exist several key knowledge gaps that must be addressed through continued research to make Digital Twins more capable, reliable, and practical for real-world applications.

4.4.1 Data Sensing

Despite mature IoT techniques, data loss during the transfer process is still a problem due to various reasons such as software incompatibility and data fading due to external environment interferences. In addition, many types of IoT sensors collect either the same or different environment data, while their data type may not be homogenous, which can present several difficulties in the data analysis process.

4.4.2 Online Look-Ahead Simulations

Current simulation methodologies for the built environment are generally not correlated with the real-time environmental data, i.e., building performance simulations are typically carried out based on historical or synthetic data instead of seeding models with current or real conditions in the environment being simulated. Such offline simulations typically reduce the accuracy of the predictions produced by simulation models, in comparison to those that are generated by models seeded with real-time data.

4.4.3 Control Strategy Optimization

In terms of control strategy, humans still play an important role in current state-of-the-art implementations described in previous studies. Such decision making, for example, is often based on the results obtained from considering limited scenarios. The usefulness of Digital Twins in the built environment can significantly increase through the automatic decision making and feedback loops by enabling real-time automated control with the potential to increase the number of scenarios analyzed to improve the efficiency and reliability of the control systems."

5. LEVEL 5: NEXT-GENERATION DIGITAL TWINS

The final level of advancement proposed in the ladder characterization system in Figure 1, i.e., Level 5: Digital Twins include not only real-time visualization and prediction to support decision making, but also support automatic feedback and control of the built environment. In addition to the capabilities supported in Levels 1-4, the built environment is enabled with an intelligent feedback control system that allows it to automatically take actions based on the optimized results and control strategies. This can be typically achieved by exploiting related enabling technologies such as artificial intelligence (AI) and ML algorithms. In such Digital Twins, the virtual and real-world built environments could interact with each other seamlessly.

Based on the identified capabilities of currently implemented Digital Twins in the built environment as well as the outlined knowledge gaps that are guiding current ongoing research, the expected features and capabilities of next-generation Digital Twins can be briefly summarized as follows:

- Visualization of real-time built environment data (e.g., construction progress, indoor temperature, humidity, occupants' locations, and thermal comfort)
- Predictions are based on snapshots of dynamic building information associated with real-time data sensing to support decision making.
- Automatic control feedback with optimized management strategies to introduce interventions in the built environment.

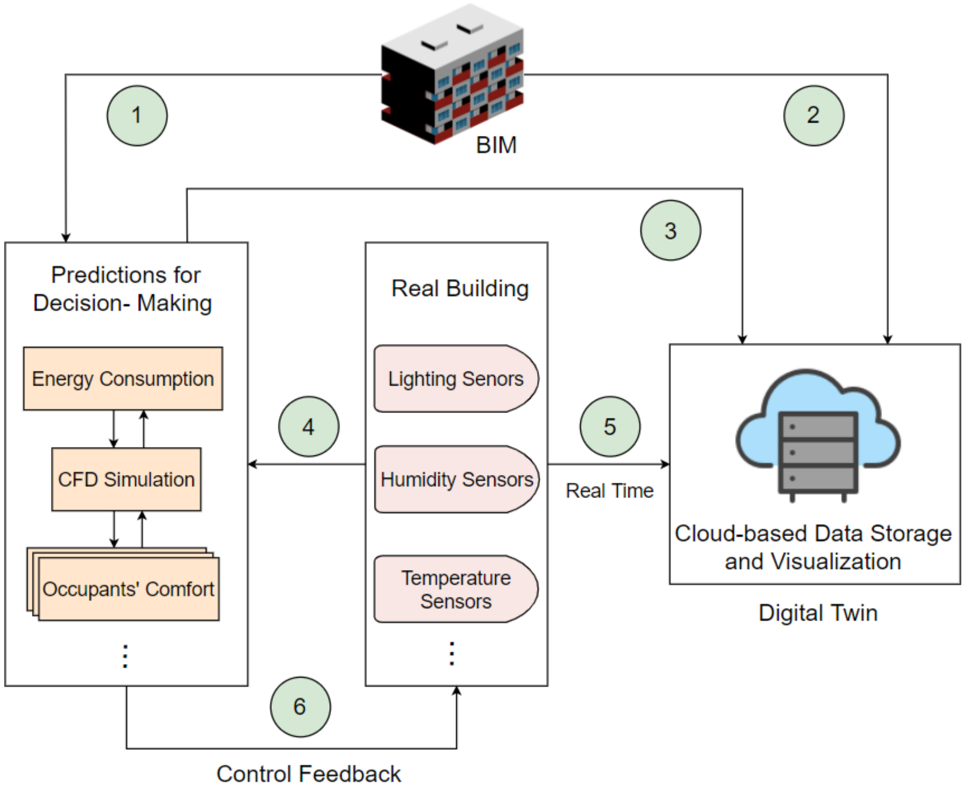
In general, the ideal next-general Digital Twin must have the capability to support different scales of buildings, starting from a single building to city-scale building stocks, with increasingly more elements to be considered as described below.

5.1 Single Building Scale

Figure 2 shows an example of the expected ideal Digital Twin for building indoor environment management in a single building. In this case, specific indoor environmental data of the real building should be collected adequately without any time delay through IoT techniques such as wireless sensor networks. The collected data should be homogeneous to be integrated and utilized to predict the real-time indoor environment or the occupant's comfort. For example, the evaluation of building energy performance, CFD simulations for indoor thermal flow prediction, as well as occupants' thermal comfort prediction could all be used as the basis for decision making in the building management process.

In order to obtain accurate results from simulations or predictions, the information extracted from the BIM model is very important since it would provide not only geometric but also semantic information to eliminate data loss with high efficiency. In addition, a certain level of decision-making strategies should be included in the control system to minimize the participation of humans in the control loop. Specific commands are then expected to be sent to the control system (e.g., HVAC, lighting systems) to achieve a certain level of automated indoor environment maintenance.

Moreover, based on the underlying BIM models, real-time visualization platforms are expected to show the on-going status of the indoor environment, which could provide a better insight of the building status to the managers, thus significantly improving the efficiency of the building system control, facility management, and maintenance.



① BIM model for supporting simulations and predictions

② BIM model visualization on cloud

③ Visualization of simulation/prediction results on cloud

④ Real-time indoor sensing data to support simulations and predictions

⑤ Real-time sensing data visualization on cloud

⑥ Simulation/prediction results feedback to support automatic building system control

FIG. 2: Example of the ideal Digital Twin for single building indoor environment

5.2 Community Scale

In terms of multi buildings scale such as a small community, additional efforts are required for the extension of the next-generation Digital Twin concept. For example, the communications between different buildings should be well established in an efficient way so that the whole community could share real-time data and be better managed as a whole (Paterakis et al. 2016, Shafiullah et al. 2017). In addition, interfaces to a wide variety of data sources (e.g., renewable energy systems) are also essential in case of any community-level deployment of such systems (Celik et al. 2018).

5.3 City Scale

When it comes to a city scale, in addition to those capabilities required in community-scale Digital Twins, tracking the mobility of individuals is another important required capability. As citizens commute frequently across a city (e.g., from residential to commercial districts during working hours), urban systems such as traffic and energy and their associated interplay play a significant role in achieving smart cities.

6. SUMMARY AND CONCLUSIONS

This paper presented a comprehensive review of the evolution from BIM to IoT enabled Digital Twin implementations in built environment. A total of 123 papers from a wide group of relevant journals and conference proceedings were reviewed. Based on the observations gleaned from the reviewed paper contents and the associated the authors developed and proposed a ladder classification system to characterize the development of the technologies from BIM to Digital Twin in an organized taxonomy. The reviewed articles were classified according to their application levels associated with the developed taxonomy.

It was found that most of the previous studies in the literature classify well under Levels 2 and 3, which are BIM-supported simulations and BIM-IoT integration for built environment management. Further classifications were also carried out based on the research domains of the studies based on the building life cycle, such as building concept design, construction process, building performance evaluations, indoor environment monitoring, and operations and management.

Based on the enabling techniques embedded in the previous studies, the authors summarized the current state-of-art Digital Twin related techniques in different aspects, including monitoring, prediction, and improvement. Based on the identified knowledge gaps and current research priorities, the authors proposed the expected features and capabilities of an ideal next-generation Digital Twin for single building indoor environment management as a reference for ongoing and upcoming research in the field and discussed the required extensions for multi-building and city scale Digital Twins.

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