TRENDS IN DIGITAL TWINNING FOR DESIGN, OPERATION AND MAINTENANCE IN NON-RESIDENTIAL BUILDINGS: A SHORT REVIEW FROM LITERATURE

Z. Wang, L.C.M. Itard and A. Meijer
Delft University of Technology

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SUMMARY

With the organizational and monitoring processes having been progressively transferred to digital for decades, digital devices are increasingly applied on the market of building design and operation. As a result, digital twins are emerging in the architecture, construction, (HVAC) engineering and facility management fields. This report first introduces the background, history, and recent trends in the application of digital twins with a detailed explanation of Digital Twins (DT), Building Information Modelling (BIM), and Internet of Things (IoT) and how they are intertwined. Secondly, the modelling and framework of digital twins application in buildings are described. Thirdly, several cases related to digital twin applications reported in scientific literature are presented and shortly analysed. It is concluded that when developing digital twins for residential buildings it could be useful to look at applications in non-residential buildings, especially on the aspects of standardization and use of BIM and models. In this report only scientific literature has been consulted and no non-published in-company developments.

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1. INTRODUCTION

The main incentive to the development of digital twins in relation to residential buildings' energy systems is the wish to be able to verify and steer building's performances in view of guarantees, to underpin financial constructions and to generate predictions relating to continuous commissioning, energy-saving, and diagnosis. According to the literature, 10-30% of energy could be saved yearly this way. Digital twins are used in this context for (automated) analysis, diagnosis, and optimization. At the moment, there are used almost exclusively in large non-residential buildings (offices, schools, hospitals). What are the status and capabilities of these digital twins that could be useful for residential buildings and could help to achieve the whole energy saving potential in dwelling's energy systems?

The popularity and development of digitization are spreading fast. With the organizational and monitoring processes having been progressively transferred to digital for decades, digital devices are increasingly applied on the market. For instance, according to Van der Meulen nearly 8.4 billion Internet of Things (IoT) and smart devices were connected in 2017 which represents an increase of 31% from the previous year (Meulen 2017). Moreover, in the prediction by Vailshery (Vailshery 2021) it is estimated that the total installed connected IoT devices worldwide will be increasing to 30.9 billion units by 2025, which is a significant jump from the 13.8 billion units that are expected in 2021.

The phenomenon of the continuously emerging applications of digital twins is the result of this digital transformation. Digital twins are not a new concept. However, there is no strict definition of digital twins. Different definitions have been presented by many researchers. It is generally agreed that the concept of a digital twin was first introduced in 2002 in the university course by Grieves(Grieves 2014). Digital twin was defined in 2010 as an "integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin" (Shafto et al. 2012). Therefore, it was initially used in aerospace and manufacturing industries and has been applied to different fields and industries and is extensively used to implement real-time diagnosis and analysis in case of system breakdown. As buildings are operating throughout a long service time of at least a few decades, the malfunctions and degradations in performance are inevitable during their service life. Therefore, applying real-time monitoring and diagnosis is crucial for building industries, which is actually pushing their development.

A specifically interesting development in the field of buildings is Building Information Modeling (BIM), in which various semantic information is used in a common data environment to build models in order to accelerate the digitization in the building architecture, engineering, construction and operation industry (Pan, Zhang, and Skibniewski 2020). In recent years, the cloud BIM has been developed to promote deeper cooperation with various project participants, providing cloud spaces for gathering, managing, and sharing information. It creates an opportunity of using BIM as a data repository to store large quantities of data collected from sensors, building management tools, inputs and documents. It also creates a potential opportunity for BIM to play a significant role in information delivery and management during the entire building lifecycle. The value of BIM from IoT integration perspectives lies in its powerful ability to create an information loop among different systems, participants, and phases (Dave et al. 2018). Some studies have highlighted the effective use of BIM-IoT integration to create digital twins in improving the efficiency of building operation and constructions(Boje et al. 2020; Jia et al. 2018). However, most of these researches are still at the concept stage.

As a result, this report explores the current usage of digital twin driven solutions in non-residential buildings for diagnosis, maintenance, simulation and prediction. The digital twins may enable the detection of behavioural anomalies, which are potentially attributable to faults within the equipment. Fundamentally, this can help to influence or determine rules needed by the system. While many existing publications have focused on non-residential building applications, there is an increasing interest in the residential building domain.

The present report addresses developments in non-residential buildings that are expected to be of interest to the residential sector. Most existing digital twin implementations are application- or equipment-specific, and as such, there seems to be little systematic way to select, design, or implement them. As a result, the focus in this report is placed on investigating the following questions:

1. What are the recent trends in the application of digital twins in buildings? (Chapter 2)
2. Which methodologies can be used to set up digital twin environments for buildings? (Chapter 3)
3. Are there specific frameworks and strategies how to integrate digital twins in building design and operation? (Chapter 4)

In this report, only descriptions from scientific literature have been addressed.

2. HISTORY AND RECENT TRENDS IN THE APPLICATION OF DIGITAL TWINS

2.1 Digital twin

The digital twin (DT) is a concept that can be applied to many fields and technologies. In 2002, the concept of a digital twin was first introduced in a university course on Product Lifecycle Management (Grieves 2014). Initially, it was published in the field of aerospace and was described as "*a reengineering of structural life prediction and management*" (Tuegel et al. 2011), later broadly applied in product manufacturing (Schleich et al. 2017) and recently extended into smart cities (Neda Mohamaadi and Taylor 2017) and buildings(W. Wang et al. 2020). The term "cyber-physical integration" has been created later for DT (Qi and Tao 2018) (Yuan, Anumba, and Parfitt 2016). The term "System of Systems" is also referred (Schluse et al. 2018), which purposed to depict the conditions of scale and complexity to sustain systems and to communicate data in a more effective and intelligent manner.

For this report, the definition by Lin Zhang is used that "a digital twin can be defined as follows: A digital twin is a digital model of a physical object, the model can evolve in real-time by receiving data from the physical object to keep it consistent with the physical object throughout its whole life cycle. Based on a digital twin, analysis, prediction, diagnosis, training, etc. (i.e., simulation) can be performed, and the simulation results are fed back to the physical object, thereby helping to optimize and make decisions on the physical object." (Zhang, Zhou, and Horn 2021)

The approach presented by Grieves (Grieves 2014) is adopted, introducing a comprehensive view of the complex system of a digital twin. Thus, the main DT components considered here are, see also Figure 1:

1. The Physical components
2. The Virtual models and
3. The Data that connects them

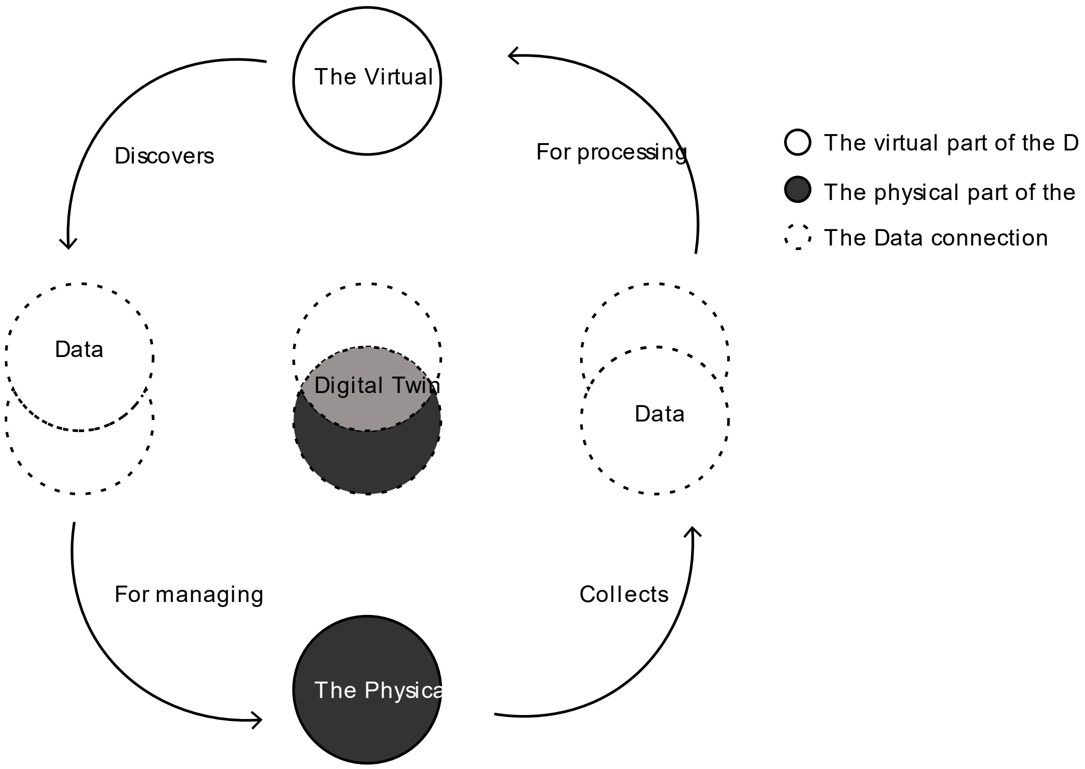

Figure 1. The paradigm of digital twins (Boje et al. 2020)

The various forms of "Data" provide the connection between the physical and virtual parts of the system. In Greves description, he considers the data from virtual part to system part require several transformations such as processing information and storing, engineering, and managing knowledge across the digital model. In the opposite direction, the data from physical to virtual could consider to be raw and require processing as well. Therefore, the data has been collected by the physical part and sent for processing. In return, the virtual part applies its embedded engineering models and AI to identify needed information for managing the daily usage of the physical part in return.

2.2 Building Information Modeling (BIM)

By the definition of the US National Building Information Model Standard Project Committee(Azhar, Khalfan, and Maqsood 2012) BIM is "a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its life cycle; defined as existing from earliest conception to demolition." Therefore, the BIM has been described as "an overarching term to describe a variety of activities in object-oriented Computer Aided Design (CAD), which supports the representation of building elements in terms of their 3D geometric and non-geometric (functional) attributes and relationships." (Ghaffarianhoseini et al. 2017). BIM is not only a 3D CAD modelling (Azhar, Khalfan, and Maqsood 2012; Ghaffarianhoseini et al. 2017), the essential function of BIM is to be a repository of information such as material type, cost, area size and installation method, working as a design model and information- rich model to enhance collaboration in the architecture, engineering, construction and facilities management community. Moreover, BIM can also be used to support and optimize the development of construction by simulating operations management on the site (Coraglia et al. 2017).

BIM has been developing from the 1990s to the present by accumulating more information on it (Sacks et al. 2018). In the first maturity version of level 0 BIM in the 1990s, it only used early CAD modelling software, so that the capability of data and information sharing was very limited due to the limitation of technology at that time. Level 1 BIM emerged during the 2000s. During this period, the 3D CAD modelling and common data environment started to be used for digital data sharing by companies. However, the capability of model sharing with project teams was still missing. In the 2010s, Level 2 BIM has been developed for 3D (construction elements, quantities), 4D (time), and 5D (cost) data sharing by using a common file format. Currently, most companies are still at level 1 or level 2. However, level 3 BIM is being created with integrated BIM and lifecycle management. A centralized repository is then used to store the design model to assure collaboration throughout the building lifecycle (Goodhew 2016).

The 4D modelling process of BIM has added on a virtual representation of a new dimension (time), which means that all aspect of the BIM such as cost, 3D models, facility management, and safety issues, etc. are able to be viewed, analysed and presented in a comprehensive and integrated time perspective. Much recent research (Khajavi et al. 2019; Ghaffarianhoseini et al. 2017; Minoli, Sohraby, and Occhiogrosso 2017) presented that the multiple dimension model data has been used to a new domain such as site monitoring, health & safety, or building environmental aspects and provided new methods to use these data. This in turn, brings new degrees of complexity, with more input data required by each domain. This data often originates from heterogeneous sources (tools, sensors, building management systems, etc.), which need to be correlated to existing BIM models on object levels, be consistent across project models and documentation, as well as overtime.

2.3 Internet of Things and Smart Buildings

Many studies consider the inclusion of IoT in DT, as its increased adoption rate has made devices more affordable and their applications wider. Once again, interoperability is cited as the main challenge due to the laborious efforts required to connect sensor data to DT simulations. The study in Madakan et al. (Madakam, Ramaswamy, and Tripathi 2015) defined IoT as “an open and comprehensive network of intelligent objects that have the capacity to auto-organize, share information, data, and resources, reacting and acting in the face of situations and changes in the environment.” With the development of innovative internet technologies and wireless sensor networks, IoT can collect more affordable and available data. The data can be processed and analysed by actuators using analysis-based control of the physical environments (Jaribion et al. 2018; Alam and El Saddik 2017). With the improvement of computing and communication for physical objects, high-quality services can be provided for the users through its wired or wireless communications. Therefore, the concept of smart buildings has appeared due to the breakthrough of the IoT technology, and it has been broadly applied to new constructed buildings. According to Jia (Jia et al. 2018), three primary characteristics that identify a smart building are its components, functions, and outcomes. Components are used to indicate different interconnected pieces of technical building equipment, appliances, sensing, and control infrastructure. Functions define the intelligence and effectiveness of the building by using the data collected from components and result in certain outcomes such as occupant health, comfort, diagnosis, operational costs, and energy efficiency. All these outcomes are tightly connected to society, economy, and environment.

2.4 Analogy and relationship between IoT, BIM and Digital Twins in practice

BIM and digital twins of buildings can be evaluated and compared by the aspect of application focus, end-users, composition (Khajavi et al. 2019). BIM is mainly used to facilitate the construction process, prevent design errors, increase efficient communication between the building construction team and stakeholders, and monitor the construction cost and process (Volk, Stengel, and Schultmann 2014).

Differently, the digital twin of buildings can be used for system fault detection and diagnosis (Qi and Tao 2018), building property maintenance, improvement of indoor climate conditions, optimization of energy performance (Qi et al. 2018). BIM is usually used during buildings' design and construction phases by architects, engineers and constructor (Eastman et al. 2011). Furthermore, BIM also aims at being used by facility managers for maintenance planning throughout the building life cycle until the end of service (Azhar, Khalfan, and Maqsood 2012). However, in practice this hardly happens as BIM is most often not compatible with the Facility Information Systems (FMIS) used by facility managers.

Differently, Digital twins are usually applied in the building service phases to improve the operation of buildings. Digital twins also may provide architects with valuable information for future building design, as it may unveil the improvement parts and detect flaws during the service phase of a building.

Finally, BIM usually consist of 3D CAD modelling, standard data formats such as IFC (Industry Foundation Class) and COBie (Construction Operations Building Information Exchange) to share data(Eastman et al. 2011). Alternative significant ontology using an object centred paradigm is Haystack. It was found to have more BAS systems vocabulary coverage and respond the more demand of smart building applications than IFC in the past years(Balaji et al. 2018). The other significant ontology is Brick which has been considered by industry for Smart Building applications for several years(El Kaed, Leida, and Gray 2016). At the same time, digital twins consist of 3D CAD modelling, IoTs, and algorithms for data processing and data analytics(Xu et al. 2019).

Figure 2. suggested a framework of digital twins' application in buildings by using a BIM-IoT integrated model. BIM-IoT integrated models creates a new method of collecting, storing, and exchanging data and will possibly be merged into digital twins for practical application in buildings. More specifically, the deployment of IoT largely relies on a variety of devices to detect the actual operational states in real-time. The BIM platform has the potential synergy with IoT to synchronize and store various data. After a large amount of data is interpreted and processed into the proper structure, it can be utilized to build the digital twin by mirroring the physical system in an isolated virtual environment.

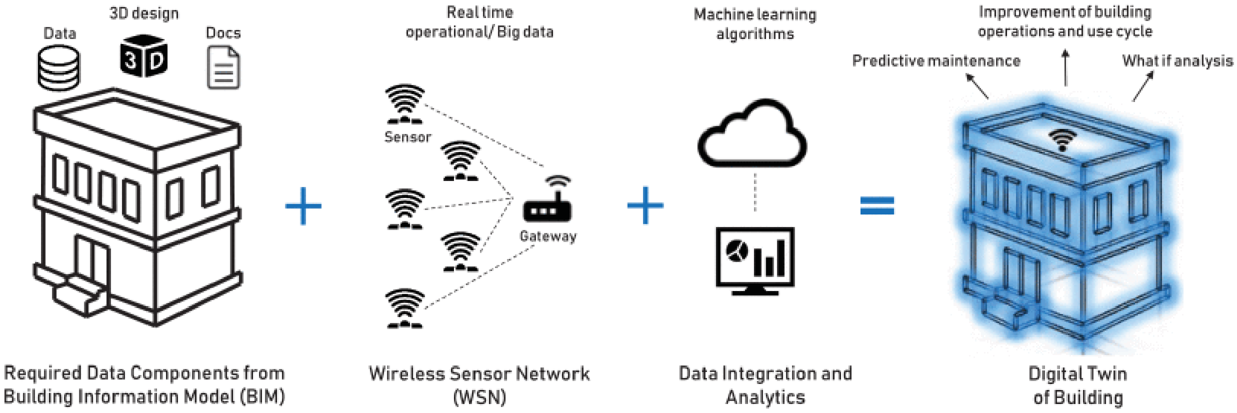

Figure 2. Essential components to create a digital twin for building with BIM and IoT (Khajavi et al. 2019)

3. METHODOLOGIES FOR DIGITAL TWINNING IN BUILDINGS

In this section, we address first the structure of digital twins, and then we focus on methods for diagnosis, fault detection, and control[1].

3.1 Frameworks and structures of digital twin applications in buildings

In their research (Tao et al. 2017) defined the digital twin of a building as the "interaction between the real-world building's indoor environment and a digital yet realistic virtual representation model of the building environment, which provides the opportunity on real-time monitoring and data acquisition." In their delineation, an indoor environment indicates information on the air temperature, airflow, relative humidity, and lighting condition, while a digital virtual one indicates computational fluid dynamics and luminance level.

According to the characteristics and theoretical basis of a digital twin, Wang et al. (W. Wang et al. 2020) proposed a framework, as shown in Figure 3. The framework consists of four parts: status sensing layer, model collaboration layer, system decision layer, and management control layer. And the driving force of the whole system is data.

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[1] Digital twins for energy prediction are addressed in the report 'Introduction to digital twins, models and parameter estimation' by Andera Thaddeus, report Task 1.3 IEBB-2 project

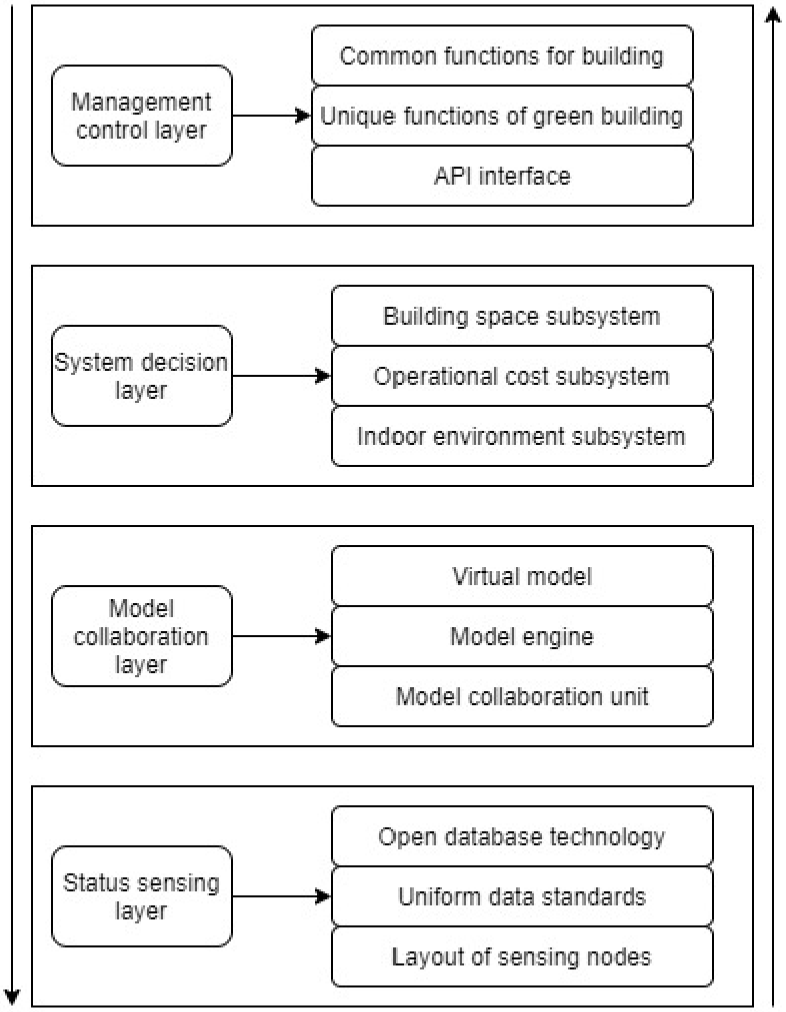

Figure 3. Detailed design of the framework (W. Wang et al. 2020)

Firstly, the status sensing layer is the lowest level of the framework, which is composed of various sensing nodes. This layer is responsible for collecting the status data of people, facilities, and environment, and preliminarily processing the data and uploading it to the corresponding database. It can also implement the control function according to instructions of upper layers. Secondly, the model collaboration layer is data-centric and responsible for the storage, searching, deployment, and management of data from both virtual and physical models. Its purpose is to compare the status differences between the virtual end and the physical entity and give real-time feedback to ensure the perfect mapping between them. Thirdly, the system decision level consists of various subsystems, which can call relevant data according to their own functions and conduct secondary processing on these data, so as to realize the control of the building. Fourthly, the management control layer is a collaborative management platform that can offer man-machine interaction functions and realize the communication management of all relevant parties. These participants can insert, extract, update, modify and view data according to their rights to support their collaborative work. In general, the proposed framework takes data as a bridge to organically integrate the above five functional layers, which establishes a data-driven building maintenance and operation system based on digital twin.

A standard data format is essential in the interoperability of digital twins since they contain various data resources. Multiple applications and system terminals with overlapping data requirements support various tasks during operation and maintenance phases. Interoperability indicates the capability of data exchange between different applications, which smooths digital twin workflows and facilitates automation. One of the main building product data models is Industry Foundation Classes (IFC) which is for building planning, design, construction, and management. Besides, in order to increase the interoperability of the building asset model, Construction Operations Building Information Exchange (COBie) was created. COBie dataset can be used to exchange data information between different software products. Especially in the BIM model, as it has the potential to synchronize and store various data for the digital twins model, a COBie file of BIM could contain plenty of information from construction to operation and management. As introduced above, alternative ontology is Haystack(Haystack 2020). Haystack uses some terms specifically to refer terminological and instance data. In the Haystack ontology, dictionaries of “name value” pairs are defined as a semantic data representation. For example, in describing an individual HVAC in a building, the “value” is used to define the HVAC and the “name” is the unique string to represent it. Same “names” are used to record instance data and referred to as “Tags”(Quinn and McArthur 2021). Another ontology Brick is also mentioned earlier. Unlick Haystack, consistent language is used to describe terminology and instance data. Brick specifically focused on description logic for describing HVAC systems which “are a family of knowledge representation languages that can be used to represent the knowledge of an application domain in a structure and formally well-understood way” (Staab and Studer 2010). Hierarchical design is used in Brick where “Classes” and “Subclasses” define varying level of detail (Charpenay et al. 2015).

3.2 Diagnosis & Fault detection & Control in digital Twin

Diagnosis and fault detection plays a significant role in applications of digital twins in buildings. Fault Detection and Diagnostics (FDD) methods are commonly classified as quantitative model-based, qualitative model-based, and process history-based (Mirnaghi and Haghighat 2020). (Figure 4)

Most of the quantitative model-based methods apply mathematical, physical models, also called white-box models’ (Kallab et al. 2017), based on energy and mass balances. These models may be building thermal models of HVAC component, as typically used in software like energy plus, TRNSYS etc.

The qualitative model-based methods look at the state of a system and its components. Most of them are rule-based and use if-then-else rules, based (Choiniere 2008) on expert rules and on measured operational states. Typically, such models take care that operational values like temperature, flow, pressure are kept within pre-set values (setpoints) and send warnings if that is not the case.

In the process-history-based methods, also referred as data-driven methods, historical data from the Building Management System (BMS) are used to estimate trends, patterns, and outliers. Patterns can be extracted from energy signatures (Belussi and Danza 2012) which consist of scatter diagrams and carpet plots for energy consumption and state values like supply temperatures. Regression methods may also be used (Wang et al. 2016) or be bonded with grey boxes energy models where the historical data is used to estimate parameters of simple models. Except for regression models, more machine learning methods, such as support vector machines (SVM), principal component analysis (PCA), and artificial neural networks (ANN) are applied to fault detection in components like sensors.

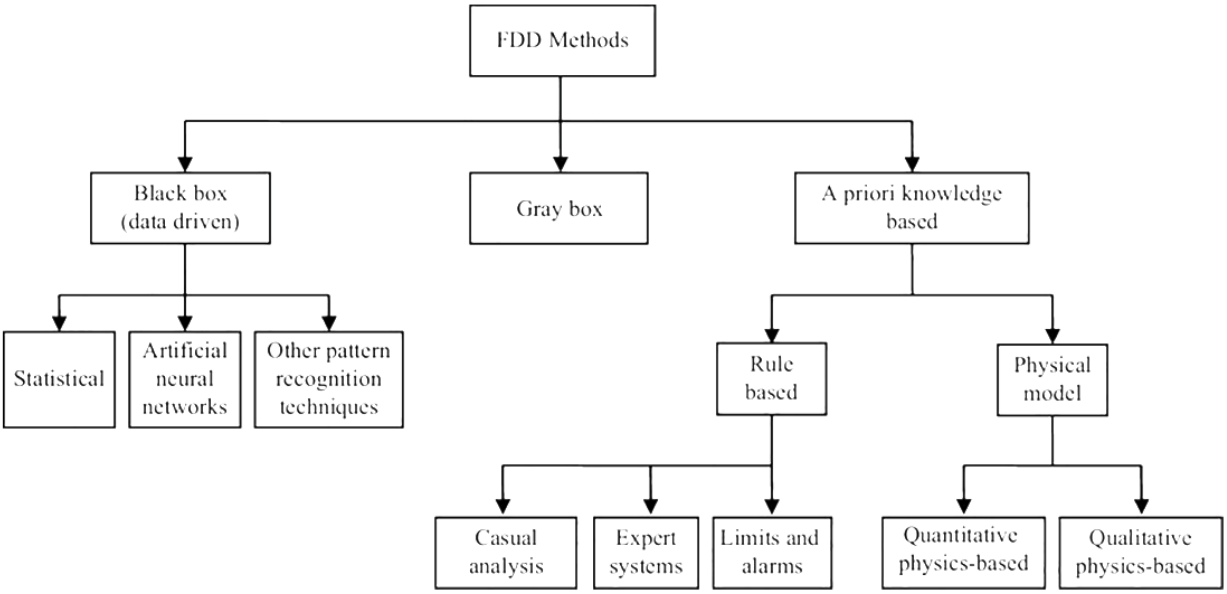

Figure 4. Classified of FDD methods (Mirnaghi and Haghighat 2020)

Between the black box models and the white box models (either physical or rule-based), there is a continuous scale of models, so-called grey models having features of both. Although the definitions are not very clear in the literature, in this report, we define grey box models as models having features of physical models but being calibrated by a continuous flow of operational data. In other words, they also can be said to be data-driven models supported by physical models.

4. FRAMEWORKS AND STRATEGIES FOR DIGITAL TWINS IN BUILDING DESIGN AND OPERATION: CASE STUDY

This section illustrates the application aspects of digital twin solutions in buildings based on a literature review in recent years. It does not pretend to be exhaustive, but just present interesting cases found in scientific literature. Four categories of applications are reported and presented in this section, including applications in indoor climate and human comfort, energy servicing, building asset management, and fault detection and diagnosis. A brief introduction and description are presented for each of these four applications, followed by the approaches used by different researchers. For each of the cases, the main idea, the applied algorithm, the collected type, analysis method, and validation method are extracted and outlined in an analytical table at the end of the chapter.

4.1 Digital twins for Indoor climate and human comfort assessment

There are few applications in this domain. The four most relevant ones are described below. Two for office buildings, one for classrooms and the other one for residential buildings.

Valinejadshoubi et al. (Valinejadshoubi et al. 2021) proposed a framework and workflow to integrate a sensor-based(IoT) system into BIM models for occupants thermal comfort and indoor climate monitoring in office buildings during the service phase and presented visualizations of a thermal condition building. This research also presented novel integrated BIM and IoT solutions with the purpose of improving the performance of building environmental management. The proposed framework explores the potential of BIM platform with sensor data to provide real-time interior thermal condition monitoring and human comfort, based on the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) standard 55 by creating a self-updating model for office buildings. Various IoT devices are used for collecting temperature and humidity data and these data are sent to the MySQL database server. This research also presented an integrated workflow to compile, standardize, integrate and visualize collected data in a BIM environment to analyse, promote interpretation and monitor data exchange. Time, location and the level of thermal comfort and discomfort based on the pre-set thresholds of the case study office room should be detected by the created system. Meanwhile, trigger and alarm transmission to the facility manager were also generated by wireless devices in real-time. The results demonstrate that this integrated system is a visually effective monitoring system for the management of environmental monitoring. The fully automated system is expected to be developed in the future to facilitate intelligent monitoring of the thermal conditions and occupant comfort in buildings to help decision-makers make faster and better decisions, which also aim to maintain and improve the level of occupants' thermal comfort.

In (Rattanongphisat and Prachaona 2017) the authors designed a monitoring platform for storing the measured indoor climate data such as temperature and humidity from an air-conditioned classroom in cooling mode to present an evaluation of interior thermal comfort with the simulation of different occupant clothes. 24/7 temperature and humidity monitoring data have been recorded by the corresponding sensors installed at various positions of the room. In order to quantitatively measure thermal comfort, the PMV (Predicted Mean Vote) comfort index and the comfort scale from -3 to +3 are used (ASHRAE). The data of cloth level were collected by a survey and the results show that long sleeve shirt with jacket and trousers are worn by a male, and short sleeve shirt with a jacket and full-length skirt for a female, who would then reach their thermal comfort at a relatively lower temperature. According to the analysis, comfort could be maintained while setting up a higher cold temperature and switching off the air conditioner intentionally before the end of the last class of the day, which could reduce energy consumption. The analysis shows that this method could save energy by roughly 18%. The main disadvantage of this research is that the results are not to be generalized to other locations and buildings.

In (Motlagh 2018) the authors proposed an IoT-enabled control mechanism for lighting in older homes to reduce power consumption. To achieve this goal, the authors developed a testbed for an IoT platform: using light sensors to monitor the indoor light variation. The authors then defined a control mechanism and compared the CSPC (Conventional System Power Consumption) of homes with the SSPC (the Smart System Power Consumption). The result showed a significant decrease in power consumption for lighting. Thus, the authors reached the conclusion that employing IoT-based control system will help reduce energy consumption in older homes.

Khajavi et al.(Khajavi et al. 2019) proposed a method for establishing a sensor network to develop a building digital twin model of an office building. The author aimed at lowering maintenance cost, operation cost, energy consumption, and tenants' comfort. Specific environmental factors of the building façade (i.e., light, temperature and relative humidity) are collected and analysed in this research. The step-by-step framework was introduced by utilizing a limited sensor network and can be utilized to create a more comprehensive digital twin of a building façade and interior. Therefore, different types of sensors and communication protocols are used. The technical obstacles of a digital twin application in buildings were also explained in detail, such as sensor communication, location, batteries and numbers. Moreover, the applicable solutions were also described. This research suggested a framework to decide the sensor arrangement on a building façade to enable a digital twin and discussed the benefits of the digital twin in buildings.

4.2 Digital twins for Energy Servicing

Most literature on this subject is about the prediction of electricity consumption in relation to smart loading and unloading of batteries in systems with PV panels and for electric vehicles. We are not reporting on this because:

- The purpose of studies on PV systems, batteries and electric vehicles relate to the optimization of smart grids rather than buildings
- The digital twins supporting these applications are mostly based on black-box models and do not use building models extensively

However, one digital twin application was found relating to the management of electrical peak load and controlling of building energy consumption in homes.

Naeem Al-Oudat (NaeemAl-Oudat 2019) proposed a method for energy management of electrical appliances at the peak of consumption, protection of electrical appliances against destructive currents and reducing costs that consumers have to pay. The authors developed a device that is connected with each household device powered by electricity, and during 24 h it examines the performance of electrical appliances within different time ranges, calculating the amount of energy consumed by smartly processing the collecting. To perform computations in this machine, a small board is designed using EasyEDA program that consists of a microcontroller, WiFi module, flow sensor, and power supply. The problem with this approach is that in the end the consumer is asked to not use some electrical appliances during the peak. To overcome this problem, a list of electrical appliances that can be disabled at the peak of consumption is presented to the consumer, using the list and the rules provided by the Electricity Distribution Company, which includes the price list of the amount of electricity consumed at different consumption ranges, and gives the user the information to modify consumption patterns. The authors have not presented an algorithm in this paper but compared the impact of using the machine with not using the device with a graph showing price-to-energy ratios.

4.3 Digital twins for asset monitoring and management

In the field of asset monitoring and management, three relevant recent papers were found, two for office buildings and one for a hospital.

(W. Wang et al. 2020) analysed the characteristics and theoretical basis of green building maintenance system (GBMS) and a new digital twin(DT)-based framework for GBMS (DT-GBMS) has been proposed.
This DT-GBMS consisted of three parts, which are virtual twin, prediction twin, and control twin, as introduced in the Framework section. Firstly, the model maps the physical entity in the virtual twin. Secondly, the prediction twin refers to the capability of predicting the future state of physical entities based on learning from a large quantity of historical, existing, and integrated network data (INDL). Machine learning is used for data analysis. Thirdly, the virtual model is synchronously updated with the actual state data of the physical entity by the control twin . The issue of insufficient informatization

and automatic management of green building maintenance are partly solved by this proposed framework. The detailed design of DT-GBMS is different depending on practical usage. The feasibility of the proposed framework is verified by Bentley Systems software which is using sensors and a 3D laser scanner (NavVis M6 mobile scanner) to tag and label the sensors. The result of this research indicates that the DT-BGMS has the potential to reflect the real-time status of green buildings accurately and also to improve the efficiency of green building maintenance through automatic management. Various objects in the model are identified and classified in this prototype framework by asset identification and registers labels. The asset data is stored in the corresponding database, and barcodes are placed on each physical entity. By scanning the barcode label, staff can locate the facilities and query asset configuration files which can provide detailed descriptions of assets, as well as asset management data (e.g., inspection time and inspection records). At the same time, the information about assets can also be inputted by staff based on their own authority, such as 'the refrigerator fails to work'. And this information will be timely notified to the manager.

Peng (Peng et al. 2020) propose a "continuous lifecycle integration" framework according to the digital twin(DT) concept and "early movement" of the general contractor to solve complex problems in large public buildings. By collecting the static and dynamic data from the design, construction, pre-O&M (operation & maintenance) phase up to the O&M phase and building a DT center consisting of a DT software system with real-time visual management and AI diagnosis modules, the managers acknowledged the detailed status of the whole building by visual management and received timely facility diagnosis and operational suggestions sent from the digital building. Figure 5 shows visual management-centred major components of the system and their operating logic.

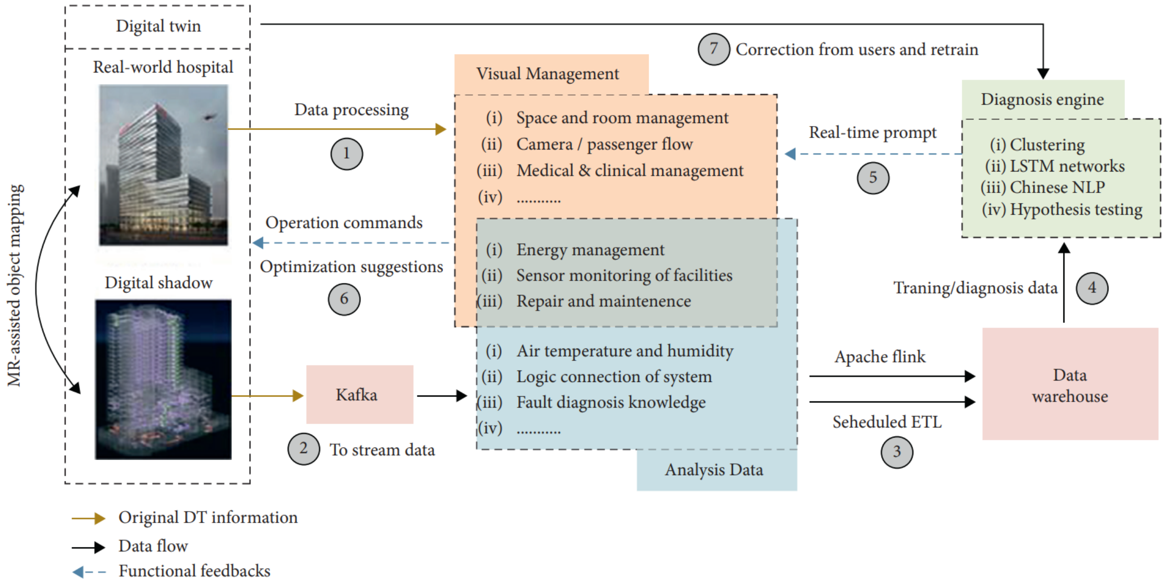

Figure 5. The operation logic of major components of the DT system (Peng et al. 2020)

In order to help to check the mapping of the digital twin to the real world, the real-time visual management, Mixed Reality (MR) was developed on the iPad tablet. It can seamlessly overlap virtual scenarios upon real entities and display them in optical equipment. In the visual management part, on-site managers, such as alarming sensors, predicted machine fault risks, unhandled repair requests, the trend of passenger flow, and monitoring videos at the clinical areas, etc. are displayed on the hospital overview screen. Applied to a large hospital in China for a year, this method achieved desired results: reducing energy consumption, avoiding facility faults, reducing the number of requested repairs, and enhancing the quality of daily maintenance work. The research also posed three major challenges while implementing the method: the technical problems caused by the lack of professionality of the software, the financial problems, as well as how to balance between the system function and the information safety.

Jafari (Jafari et al. 2020) presented a novel architecture for building control. This research integrated the existing asset management theory with building simulation technology for the improvement of maintenance efficiency and operational control schemes. The optimization evaluation is defined by a building performance, value and energy usage. IoT devices are used for collecting building assets data and real-time data are accessible at all times.

As shown in Figure 6, this digital twin covers several different types of models such as physics-based, statistics-based, process-based or a combination. The BIM provides the structural and informational foundation of a built environment, which is integrated with a dynamic model. Combining BIM model with EnergyPlus yields energy consumption of building under different internal and external conditions. This combined model has the building's physical make-up (floors, zones, envelope, materials, etc.), all associated mechanical systems (heating, cooling and ventilation, etc.) and occupancy data and schedule. The model can calculate the heating and cooling loads necessary to maintain thermal control setpoints, conditions throughout a secondary HVAC system and coil loads, and the energy consumption of primary plant equipment. The extended combined white box model of a built environment can further cover all building accessories and equipment (e.g., air compressors, plug-ins) that consume energy.

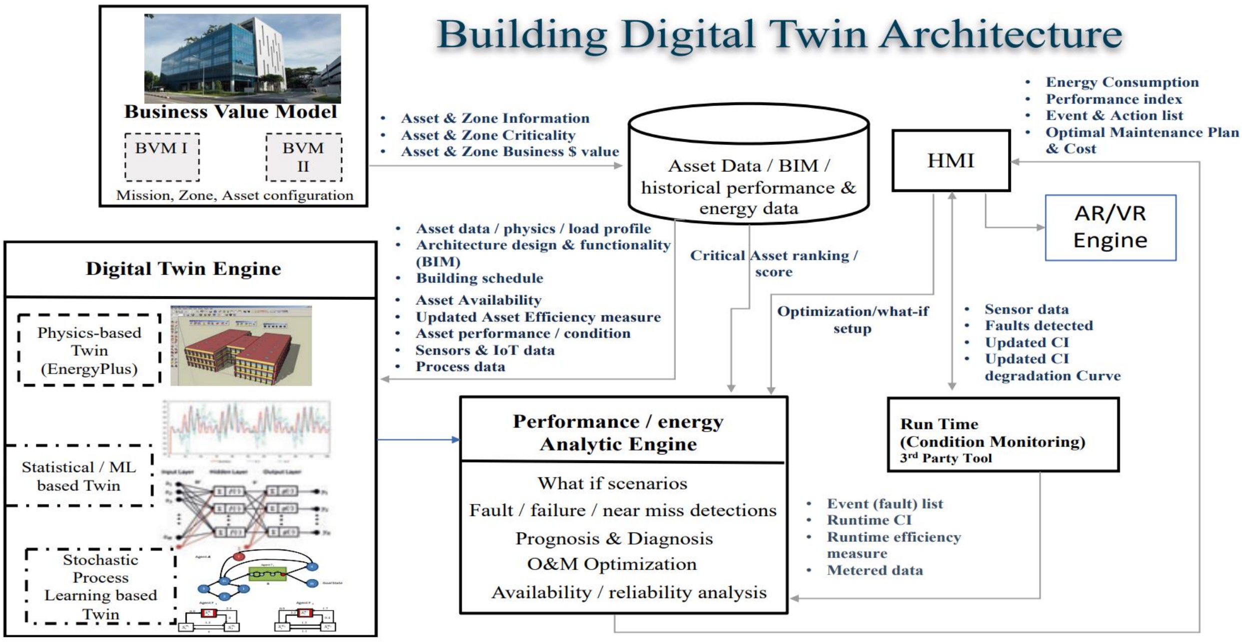

Figure 6. Digital twin architecture (Jafari et al. 2020)

From the functional contributions of the asset to the entire business objective of the system, the asset's value is evaluated. The paper provides illustrative examples of the typical public building in the model, which consists of digital twin, analytics and Business Value Model engines, and a portal for data exchange based on real and simulated data. The author also proposed how the platform can serve the operation and maintenance objectives of existing and new buildings.

4.4 Fault Diagnosis

There is much more research on digital twins for fault diagnosis. These papers were very detailed in methodology description, algorithm application, and result verification. The chosen papers almost covered all popular fault diagnosis method developed recently, such as using Diagnostic Bayesian Networks (DBN), Convolutional Neural Network (CNN) and Bayesian Changepoint detection (BCD). Case study in one of the papers was an educational building while the 3 other papers refer to office buildings.

In a study by Taal (Taal and Itard 2020), a generic Fault detection and diagnostics (FDD) architecture is developed, which incorporates a systems engineering approach with data-analytics and combines FDD with energy performance diagnosis. An HVAC system consists of trade components and aggregated systems built from these components. The architecture of the HVAC systems can be derived from a process and instrumentation diagram (P&ID) usually set up by HVAC designers. All possible faults and symptoms can be extracted in a very structured way from the P&ID and are then classified in 4 types of symptoms (deviations from balance equations, operational states, energy performances or additional information) and 3 types of faults (component, control and model faults). Symptoms and faults are related to each other through Diagnostic Bayesian Networks (DBNs), which work as an expert system and should be set up once in a time to conform to the P&ID of the specific HVAC system. Symptoms and faults are extracted automatically from data from the BEMS, which is fed to the DBN model. This digital twin consists, therefore, of a symptom identification twin, based on the P&ID model and a fault identification twin, based on the DBN. The framework was applied in historical data of a school building.

(Zhou et al. 2021) established a multi-fault decoupling diagnostic model for a variable refrigerant flow air-conditioning system, especially considering the system's unsteady defrosting process and sensor faults. The applicable and reliable FDD (Fault Detection and Diagnosis method to diagnosis VRF (Variable Refrigerant Flow) system gradual fault with defrosting process and sensor faults based on CNN (Convolutional neural network) has been proposed. A series of experiments have been tested under multiple operating conditions in different common soft faults (refrigerant overcharge, refrigerant undercharge, outdoor fouling, indoor fouling, and sensor fault) in order to verify the reliability in VRF system. The confusion matrix, geometric mean accuracy (GMA), false alarm rate (FAR) and other indicators are used to evaluate model diagnosis results of the collected fault and normal operational original data samples. Several outcomes are concluded based on above experiments. At first, it is especially needed to establish an unsteady-state data model. Because there exists model mismatch and diagnostic gaps in the actual application of the steady-state data model, due to the unsteady-state defrosting process. Secondly, the proposed CNN model has an ability to enhance the fault decoupling performance of the unsteady-state defrosting process concluded from the diagnosis result of introduced common fault data. The CNN model is superior to other models. Thirdly, to compared with DT model, SVM model and the MLP model, the proposed CNN model still has better performance in multi-fault coupling diagnosis considering defrosting and sensor fault.

In the research by (Xie et al. 2020), a digital twin enabled asset condition monitoring and anomaly detection framework. A Bayesian online changepoint detection methodology is tentatively embedded to reveal suspicious asset anomalies real-time, due to it can be used without requiring any conjecture prior knowledge about the normal or anomalous conditions. A demonstration on cooling and heat pumps is developed and implemented at the Centre for Digital Built Britain (CDBB) West Cambridge Digital Twin Pilot. There are two sub-tasks of the proposed detection framework. First, implement the Bayesian online changepoint detection in order to find which underlying symptom parameters of sequential sensing data are suspected of changing instantly. Second, distinguish change points caused by routine operations and real anomalies. The research result indicates that the proposed framework can continuously monitor the condition and detect anomalies for a single asset supported by the data management capability provided by the digital twin. This research proves the proposed framework can improve efficiency and automation in operation and maintenance management.

In the research conducted by (Lu et al. 2020), a digital twin(DT)-enabled anomaly detection system for monitoring and its data integration method are proposed. This paper also presents a novel industry foundation classes (IFC)-based data structure. A set of monitoring data that carries diagnostic information on the operational condition of assets are used. Building DT is used for diagnostic, and asset run under changing loads determined by human demands. A Bayesian change point detection methodology that handles the contextual features of building operation data is adopted to filter and identify contextual anomalies by cross-referencing with external operation information. The heating, ventilation, and air-cooling (HVAC) system of the centrifugal pumps are used as a case study to demonstrate the approach. The result indicates and proves that the DT-based anomaly detection model can continuously detect anomalies for pumps which contributes to efficient and automatic building asset monitoring in operation and maintenance.

4.5 Summary of cases

Table 1 summarizes the digital twins found in the case studies and clarifies their relationship with IoT and BIM.

Table 1. Summary of the digital twin case study

Reference	Purpose	BIM	IoT Devices	Collected Data / Building function	Data type	Analysis method	Algorithm	Validation
Chen Wu et al. 2019	Interior climate & Thermal comfort	Yes	Yes	BEMS, Indoor climate data/Office building	Environmental lighting, ambient temperature, relative humidity, air quality, electricity, cloth level	PMV	No	No
Rattanongphisat and Prachaona 2017	Interior climate & Thermal comfort	No	Yes	Indoor climate data/ Classrooms	Temperature, humidity, cloth level	PMV	No	No
Motlagh 2018	Interior climate & Thermal comfort	No	Yes	Indoor light/ Home	Lighting	Comparing conventional system power consumption vs smart system power consumption	If, else algorithm for lighting and energy consumption	No
Khajavi, Motlagh et al. 2019	Interior climate & Thermal comfort	Yes	No	Inside & outside data of the building façade/ Office building	Environmental lighting, ambient temperature, relative humidity	Data collection, visualization and testing.	If, else algorithm for sensor mesh optimization	Calculation of error correction coefficient for each sensor
NaeemAl-Oudat 2019	Energy Servicing	No	Yes	Electrical appliances, power supply/ Home	Electrical consumption	Comparing the graph of impact of using the machine with not using devices	None	No

W. Wang et al. 2020	Asset management & maintenance	Yes	Yes	building system, Historical, existing and integrated network data,BEMS/ Office building	Energy consumption, building property	Comparing simulation and existing data	Integrated network data learning	No
Peng et al. 2020	Asset management & maintenance	Yes	Yes	Building System, Asset management/ Hospital	static and dynamic data from the design, construction, pre-O&M (operation & maintenance) phase up to the O&M phase	Comparing simulation and existing data	K means cluster	No
Jafari et al. 2020	Asset management & maintenance			Asset management, BEMS/ Office building	building IoT and their real-time conditions, occupant schedule, heating cooling loads, historical performance &energy data	Performance/ energy analytic engine	Stochastic model, Neural network	Deviation from linear regression
Taal and Itard 2020	Fault detection & Diagnosis	No	Yes	HVAC systems, BEMS/ School	HVAC operation & maintenance	Symptoms and faults identification twin method	DBN model	Result testing of detected fault and simulation
Zhou et al. 2021	Fault detection & Diagnosis	No	Yes	HVAC systems, BEMS/ Office building	HVAC operation & maintenance	Neural networks	Neural networks, SVM, MLP, CNN	Result testing of mismatch rate
Lu et al. 2020	Fault detection & Diagnosis	Yes	Yes	HVAC systems, BEMS/ Office building	HVAC operation & maintenance	Symptoms and relevant information matching	Bayesian online changepoint detection methodology	Result testing of detected fault and simulation
Xie et al. 2020	Fault detection & Diagnosis	No	Yes	HVAC systems, BEMS/ Office building	HVAC operation & maintenance	Symptoms and cross-referenced matching	Bayesian online change point detection methodology	Result testing of detected fault and simulation

5. CONCLUSION AND FUTURE PERSPECTIVE IN RESIDENTIAL BUILDINGS

5.1 Conclusions

Literature review indicates that most of the applications in digital twins of buildings are currently focusing on public buildings. Among this literature, the amount of digital twin applications in indoor climate and human comfort and energy servicing is relatively small. Only limited cases could be found and most of them only introduced a general method and framework without deeper analysis. The number of digital twins used for building asset management and building system fault detection is relatively large. Especially in the building system fault detection field, machine learning and statistical methods have been broadly applied, and the papers usually provide deeper descriptions and discussion about applied algorithms and analysis.

In summary, this report presented several aspects of digital twins according to the applications proposed in the literature.

At first, a detailed framework of the digital twin containing a physical model, a virtual model, and connection data were described under the integration of BIM, IoT, and Digital twins. The application of digital twins in buildings could make the management less susceptible to human cognitive errors during building service time. IoT devices are deployed to collect real-time data about the actual status of the building operation or construction process with little manual interaction. The rich data source from IoT serves as a foundation to construct digital twin models and has a great potential to reduce model calculation time and to help save energy.

Second, there is a huge opportunity of using digital twins throughout the entire building lifecycle from design, construction, operation until the end of service. Moreover, static information and dynamic data can also be integrated as a unified DT system, including building geometry model, attached property information, HVAC systems, repair and maintenance systems, security management system. By integrating various and huge amounts of data, the accuracy, capability, and efficiency of digital twins will also be improved by using appropriate algorithms.

Third, digital twins in buildings have the potential to provide better real-time building management, which is far more efficient than manual work. Big data services were developed as a backend to consistently provide high-resolution and real-time data. The real-time status of the buildings will be used to guide everyday management activities. With this real-time mechanism, combined digital twins and BIM model has shown much more potential than traditional BIM technology.

Fourth, Intelligent digital twins diagnosis functions—professional AI models, have been assembled as a diagnosis engine, and it works seamlessly with visual management functions. Huge amounts of dynamic integrated data also support timely facility diagnosis and operation.

However, many applications of digital twins in buildings are still in the concept and experimental stage. Integration between building system design, IoT environment, construction, and standardized diagnostic tools are still underdeveloped in digital twins implementation because of their complexity and lack of standardization. This will also play a role in residential buildings, even if the building systems and collectible data are relatively simpler than in non-residential buildings. The challenges around implementation, privacy, cost, and efficiency are still worth to further explore.

5.2 Recommendations

This report did not address recent advances made in practice. Generally, these advances are not reported in the scientific literature, and publications remain at the level of explaining the capabilities of the system. However, it is clear that a lot of R&D has taken place at companies' level and the number of commercial applications in the field of energy management systems has increased a lot during the past years, see for instance, systems like Simaxx[2], originally developed by DWA, InsiteView[3] (Kropman), and systems by Priva[4], Johnson Control[5], Schneider[6], Siemens[7], Dyseco[8] , etc… However, it is widely recognized[9] that to achieve the needed level of automated building operational management advances are needed: current models and algorithms are not quick and efficient enough to make buildings really smart, en the implementation of such systems is very uneasy and time costly.

The advances in the market of residential buildings are much less. However, there are many developments taking place in the field of home automation and sensoring for energy use and indoor climate. For this market, the following recommendation can be made: Don't reinvent

- How and what to Monitor
- What you can do with the data
- Standards and Analyses methods

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[2] https://simaxx.com/

[3] https://insitesuite.nl/

[4] https://www.priva.com/expertise/building-automation/

[5] https://www.johnsoncontrols.com/services-and-support/energy-and-efficiency-solutions

[6] https://se.com

[7] https://new.siemens.com/global/en/products/buildings/automation.html

[8] https://dyseco.nl/?lang=en

[9] B4B TKI-project Brain for Buildings, https://www.tudelft.nl/urbanenergy/research/programs/brains-4-buildings

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Authors
Z. Wang, L.C.M. Itard and A. Meijer
Delft University of Technology

Contact
https://www.tudelft.nl/urbanenergy/research/programs/iebb


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