Digital Twins implementation in Operations and Maintenance phase of a building lifecycle

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Title Page

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Abstract

The Digital twin concept which is a result of the fourth industrial revolution has led to many companies and industries to discover a competitive advantage through the improvements of processes by integrating technologies like artificial intelligent, machine learning, cloud computing, robotics, etc. In general, the AEC industry is characterised by slow adoption of new technologies partly due to the fragmented nature of the industry, however BIM tools and its associated technologies have been widely adopted in the AEC industry due to the benefits it provides in terms of facilitating exchange of information between stakeholders, efficient way in managing logistics, clash detection, scheduling etc. There exists little research about the implementation of the digital twin concept in the AEC industry and the main purpose of this thesis investigate the existing knowledge concerning the Digital Twin concept as it relates to the AEC industry.

This paper combines a systematic literature review as well as interviews with industry players to understand the current state of digitalisation in the AEC sector during the O&M phase of the buildings lifecycle as it relates the DT concept, the components of the Digital the Digital twin concept and the value the implementation of the digital twin concept provides to the stake holders in the AEC industry

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1. Introduction

Significant advancement in technology and innovations due to the fourth industrial revolution (Industry 4.0), has led to many industries adopting digital technologies like the Digital Twin Concept to discover competitive advantage by enhancing their processes (Henderson & Ruikar, 2010). Industry 4.0 is a term that is defined 'as a new level of organization and control over the entire value chain of the life cycle of products, geared towards an increasing individualized customer requirements/satisfaction (Vaidya, et al., 2018)'. In the manufacturing industry, it also refers to the integration of Internet of Things (IoT) and internet of services in an environment where industrial business all over the world connect and control their machinery, factories and warehousing facilities intelligently through a cyber-physical system by sharing information that triggers actions (Maskuriy, et al., 2019).

The Architecture Engineering and Construction (AEC) industry is generally slow in accepting and implementing new technologies compared to other industries partly due to the high degree of fragmentation (Henderson & Ruikar, 2010). However, in the AEC industry, Industry 4.0 introduced digital technologies, sensor systems, intelligent machines, and smart materials to an industry where Building Information Modelling (BIM) has increasingly become the central repository for collating digital information about a project (Maskuriy, et al., 2019). The benefits and capabilities of BIM have been proven for the design and construction phases; however, there is lack of awareness of BIM benefits in the operation and maintenance phases (Shalabi & Turkan, 2017). This is partly due to the lack of clear and validated benefits of BIM in facility management practices, the lack of integration between BIM and IoT due to problems associated with legacy formats that are not aligned (Boje, et al., 2020) and technological issues in integrating BIM and IoT to monitor assets during operation and maintenance (Becerik-Gerber, et al., 2012). Another reason for that may be ascribed to this is the multifaceted and complex challenges of asset management, and the asset management frame's alignment to the BIM information management processes (Lu, et al., 2020). However, BIM implementation has led the digitalization of the construction industry by enhancing visualization, coordination, simulation, optimization, and the ability to plot (Alaloul, et al., 2018). Efforts aimed at Integration of BIM with other sources like IT environments, cloud computing and IoT has led the transitions from the current 'react to events' practice to a 'predict the event' practice, enhanced decision making through real-time collaboration between stakeholders to ensure project delivery and enhance information flow throughout the project life cycle, optimize energy efficiency, improve safety and security etc. (Maskuriy, et al., 2019).

In order to the AEC industry to fully benefit from the digitization drive as a result of the fourth industrial revolution, it has to embrace or apply the concept of digital twins throughout the lifecycle of the built environment (Brilakis, et al., 2019). Digital twins can be briefly defined as a digital replica of a real-world entity (Saddik, 2018). A Digital Twin is more than just a BIM or a 3D model in that they serve as a source of data that can help improve the design of new assets, understand existing assets, run 'what if' simulations, verify the as-built situation and also provide a snapshot for future works (Evans, et al., 2019).

‘The global digital twin market was valued at USD $3.1bn in 2020 and is expected to reach USD $48.2bn by 2026. It is expected to grow at a Compounded Annual Growth Rate (CAGR) of 58% during the forecast period, increasing demand for digital twins in the healthcare and pharmaceutical industries due to the outbreak of COVID-19 pandemic, the changing face of maintenance, and growing adoption of digital twin solutions to cope up with the COVID-19 pandemic are the key factors driving the growth of the digital twin market (MarketsandMarkets, 2020).’ Therefore, the AEC industry needs to explore the benefits Digital Twin technologies have to offer the industry while ensuring increased productivity and efficiency. Gartner, predicts that half of all large companies will use some form of DT by 2021 – resulting in a 10% improvement in effectiveness (Pettey, 2017).’ Digital Twins technology possesses the potential to unlock economic, social, environmental, and business value for the built asset industry. The manufacturing industry has used the concept to analyse and optimize production, resulting in improved productivity and better reliability. Another industry that has exhibited the benefits of the digital twin concept in the automotive industry where it has been used to simulate material performance, temperature, and many other properties to enhance product development. (Beetz, et al., 2020)

It is for the reasons expressed above that the Centre for Digital Building Britain (CDBB) together with the United Kingdom government and other partners seeks to digitize the entire life cycle of built assets finding innovative ways of delivering more capacity out of existing social and economic infrastructure, dramatically improving the way assets deliver social services to deliver improved capacity and better public services. They hope to achieve this by building on or leveraging the benefits of information management processes, and efficiency gained during the design and construction stages through BIM ((CDBB), 2020). Combining this technology with the digital twins, IoT (sensors, advanced analytics, data-driven manufacturing, and digital economy) will ensure that the infrastructure's planning is more effective. The building is done at a lower cost and will also improve operation and maintenance for a longer lifespan. Digital Twins will ensure more effective building operation by providing real-time data integration between the physical and digital twin.

BuildingSMART International (bSI) has also joined in the efforts realizing the potential of digital transformations in the AEC industry by setting up a working group to help in setting standards for data models, standards for data management and integration and data security and privacy with respect to Digital Twin paradigm. This is due to the role it has played as a go-to place for developing open digital solutions and standards for the built asset industry with an example being the development of the Industry Foundation Classes (IFC). (Beetz, et al., 2020).

1.1. Problem Formulation

As mentioned earlier Building Information Modelling (BIM) has increasingly become the central repository for collating digital information about a project with its associated benefits and capabilities been proven for the design and construction phase (Maskuriy, et al., 2019), (Shalabi & Turkan, 2017). However, during building operation information and data are collected through various other means. These data are stored in various Facility Management (FM) information systems, for instance, CMMS (computerized maintenance management systems), EDMS (electronic document management systems), EMS (energy management systems), and BAS (building automation systems) (Becerik-Gerber, et al., 2012). However, these systems lack interoperability and visualization capabilities (Shalabi & Turkan, 2017).

Whiles the implementation and benefits of BIM and its associated technologies have been prevalent over the years both in research and practice in design and construction, research within the area of Digital Twins in the AEC industry is relatively scarce.

The goal of this thesis to investigate the current status of development and implementation of the Digital Building Twin in the AEC industry and demonstrate how digital building twins can add value to the various stakeholders involved during the operational phase of the building lifecycle by proposing a conceptual framework on how the concept can be implemented. This has led to the research question of this paper:

How can digital building twin concept add value to the various stakeholders during the operation and maintenance phase of the lifecycle of the building?

- What is the status of digitization in the operation and maintenance phase of building?
- What does the digital twin concept entail?
- What value can it provide to the various stakeholders involved?

The subsequent chapters are structured to systematically take the reader through the existing knowledge of digital twins including the historical and theoretical aspects as well as general concepts related to the digital twin concept (**Chapter 2**), it also contains efforts being made towards the adoption of the digital twin's concept in the AEC industry. **Chapter 3** deals with the methodology used in gathering data and analysing data to enable the author to answer the research question. This includes a systematic literature review of selected articles and interviews with industry professionals.

The next chapter (**Chapter 4**) contains details of how the systematic literature review was done with the help of PRISMA framework and thematic analysis of these shortlisted articles. **Chapter 5** deals with the analysis of the data acquired through the semi structure interviews.

Based and the analysis of both literature and interviews, **Chapter 6** discusses the findings which seeks to answer the problem formulations stated above.

The research concludes my summarising the whole process in **chapter 7**.

2. Digital Twins (Historical overview, Theoretical Aspects and General Concepts)

In this chapter, the existing knowledge and the necessary concepts involving Digital Twin are explored, to get an understanding necessary to proceed with the desk research. The investigation includes the exploration of the Historical Overview, the Theoretical Aspect of Digital Twins, and the research of Digital Twin in the AEC industry.

Keywords, databases where research papers and articles are found, and time frame were defined as the Start set. In this thesis, the keywords were: ‘BIM and IoT’, ‘Digital Twins Concept’, ‘Industry 4.0 in AEC, Digital Twins in AEC’, ‘Digitalisation of FM’, ‘Digitalisation in AEC’, ‘Energy Management in Buildings’, ‘Energy Management System’, ‘Product Life Cycle Management’, ‘BIM and Digital Twins’ etc. With the help of the keywords research was carried out using Aalborg University Library called Primo, Google Scholar and other databases such as Science Direct, Emerald Insight, Research Gate, ACM Digital library; where the timeframe was set to 10 years, specifically between 2010 and 2020.

2.1. Historical Overview

The concept of Digital Twin can be said to have originated around April 13, 1970, when NASA attempted to land Apollo 13 on the moon. The story is told that after the astronauts encountered a fault in the oxygen tank mid-air and radio back to the command centre ‘HOUSTON WE HAVE A PROBLEM’...

The command centre undertook a series of simulations and calculations with the help of simulators available at NASA to train the astronauts prior to their mission.

‘The simulators were some of the most complex technologies of the entire space program: the only real things in the simulation training were the crew, cockpit, and the mission control console, everything else was make-believe created by a bunch of computers, lots of formulas, and skilled technicians. - Gene Kranz, NASA Chief Flight Director for Apollo 13

What makes Apollo 13 the first real-life use case of digital twins is the ways in which NASA’s Mission Control was able to rapidly adapt and modify the simulations to match the conditions on the real-life crippled spacecraft and enable research to be done, reject and perfect strategies used to bring the astronauts back home (Ferguson, 2020).

In 2002, during the formation of the Product Lifecycle Management (PLM) centre in Michigan, Michael Grieves presented what he referred to as the ‘Conceptual Ideal for PLM’ **(Figure 1)** (Grieves & Vickers, 2016) where he briefly described, the connecting between real space, virtual space, the link for data flow from the real space to the virtual space, the link for information flow from the virtual space to real space and virtual subspace as shown below.

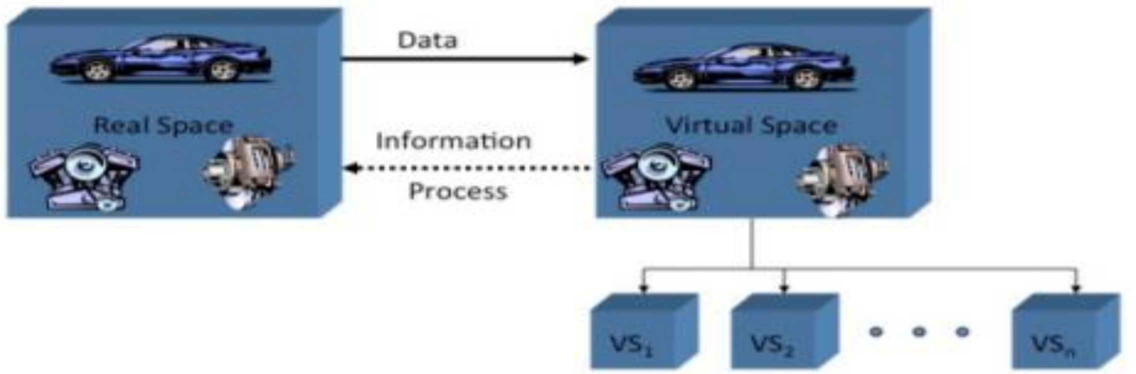

Figure 1: Conceptual Model of PLM By Dr Michael Grieves Source: (Grieves, 2006)

However, the model was referred to as the *'Mirrored Space Model'* then driven by the premise that system consisted of two systems, the physical system that has always existed and a new virtual system that contained all of the information about the physical system. Meaning there existed a 'twinning' or 'mirroring' of the real system with that of the virtual one, and vice versa and the connection existed throughout the products lifecycle (creation, production, operation, and disposal). (Grieves & Vickers, 2016)

Grieves (2006) defined PLM as "*an integrated, information-driven approach comprised of people, processes/practices, and technology to all aspects of a product's life, from its design through manufacture, deployment and maintenance—culminating in the product's removal from service and final disposal"* and described the conceptual model as 'Information Mirroring Model'. The concept was expanded in 2012 (Grieves, 2011), when Digital Twin as a term was attached to the concept due to the description given by the co-author. The model was, however, still referred to as Information Mirroring Model.

The concept became widely adopted subsequently in various industries, and an example was General Electric (GE) in 2015, built a cloud-hosted digital twins of its machines that processes information collected from sensors using artificial intelligence, physics-based models and data analytics to manage airplane's landing gear, enabling early warnings and failure predictions for several key components. This Digital Twin, combined with the engine, airframe, and other systems, scale to form a Digital Twin of the entire aircraft (Parris, et al., 2016). **Figure 2** briefly explains the components of the GE commercial platform.

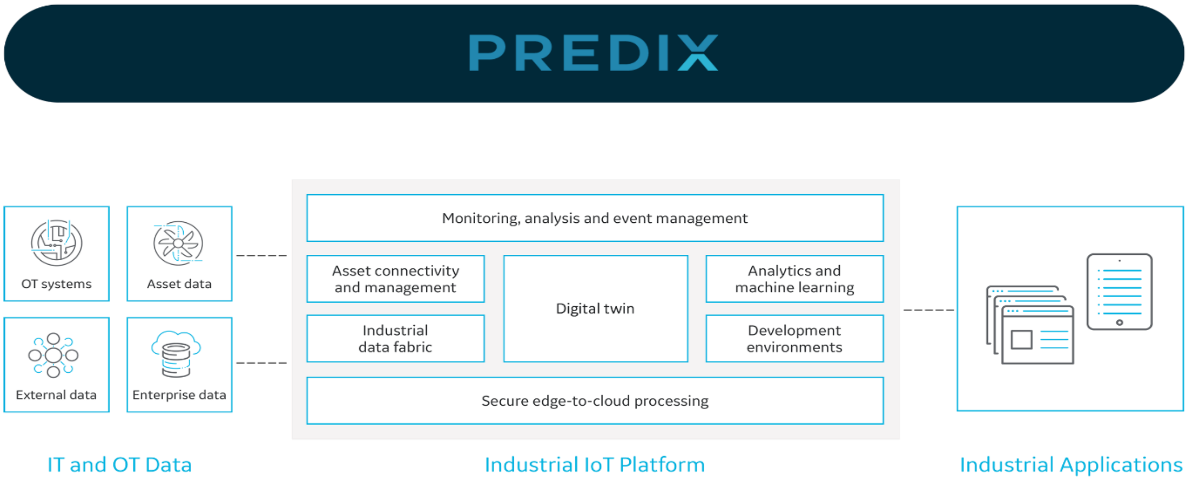

Figure 2 PREDIX DT software source (Digital, GE, 2021).

Figure 3 briefly showing the historical perspective of digital twins as it has been explained above.

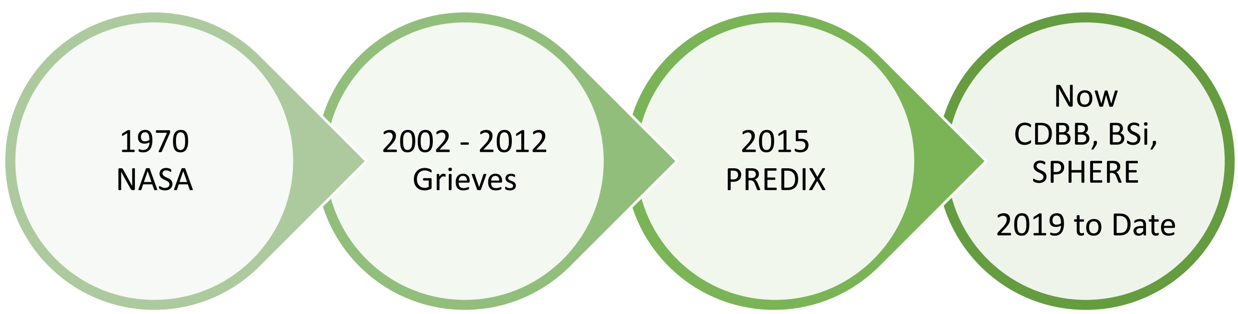

Figure 3 Historical background on the growth of Digital Twin Concept Source(self-made)

2.2 Theoretical Aspect of Digital Twins

From the brief historical background above, it is evident that there exists a wide range of the definitions and applications for what a digital twin is. (Grieves & Vickers, 2016) however, proposed that it will be beneficial to define a few terms associated with DT and went ahead and provided these definitions as follows.

Digital twin: "*the Digital Twin is a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level. At its optimum, any information that could be obtained from inspecting a physical manufactured product can be obtained from its Digital Twin.*"

Digital Twin Prototype (DTP*)*—"*this type of Digital Twin describes the prototypical physical artifact. It contains the informational sets necessary to describe and produce a physical version that duplicates or twins the virtual version. These informational sets include, but are not limited to, Requirements, Fully annotated 3D model, Bill of Materials (with material specifications), Bill of Processes, Bill of Services, and Bill of Disposal.*"

Digital Twin Instance (DTI)---"*this type of Digital Twin describes a specific corresponding physical product that an individual Digital Twin remains linked to throughout the life of that physical product. Depending on the use cases required for it, this type of Digital Twin may contain, but again is not limited to, the following information sets: A fully annotated 3D model with Geometric Dimensioning and Tolerancing (GD&T) that describes the geometry of the physical instance and its components, a Bill of Materials that lists current components and all past components, a Bill of Process that lists the operations that were performed in creating this physical instance, along with the results of any measurements and tests on the instance, a Service Record that describes past services performed and components replaced, and Operational States captured from actual sensor data, current, past actual, and future predicted*".

Digital Twin Aggregate (DTA)- *"this type of Digital Twins is the aggregation of all the DTIs. Unlike the DTI, the DTA may not be an independent data structure. It may be a computing construct that has access to all DTIs and queries them either ad-hoc or proactively."*

Digital Twin Environment (DTE*)*—"*this is an integrated, multi-domain physics application space for operating on Digital Twins for a variety of purposes. Mainly predictive (future performance and behaviour of physical asset) or interrogative (current and past histories. This would apply both for DTI's as DTAs)"*

(Grieves & Vickers, 2016)

Grieves & Vickers, (2016) also concluded that the two main types of DTP, DTI and the DTA, all which are operated in a DTE. These types are also manifested during the lifecycle of a product.

Tao, et al (2018) described how the digital twin concepts can be implemented throughout a product lifecycle.

Design Phase: Tao, et al., (2018) discussed how the Digital Twin Prototype (DTP) is used to predict the yet-to-be-built asset's performance, verify various design choices, ensure that the product meets expectations, avoid failure, and ensure product quality. With advancements in CAD software's used in designing to detailed 3D models with capabilities of being simulated for various situations provides the basis of a digital twin by creating a platform for various stakeholders to communicate effectively. This ensures the product meets expectations, avoid failure, and ensure product quality with additional simulation capabilities. (Tao, et al., 2018) classify the DTP process as ***Conceptual design***, ***Detailed design*** and ***Virtual Verification*** stages and highlights the benefits of testing a design with the use of the data of equipment, environment,

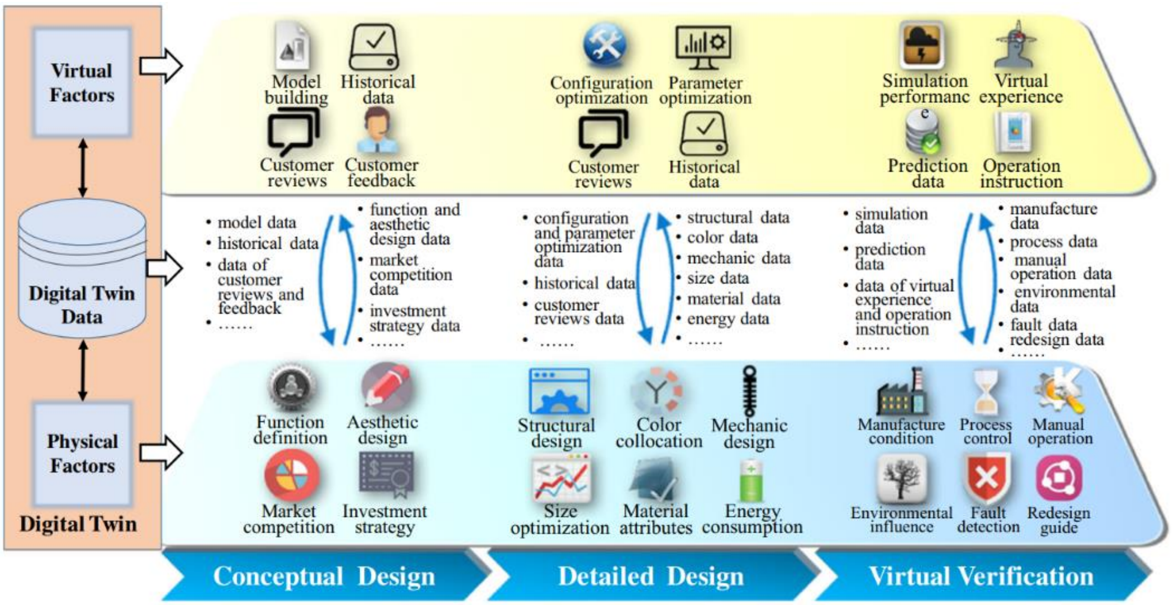

Figure 4:Digital Twin Enabled Design process for manufacturing. Source: (Tao, et al., 2018)

material, customers' physical characteristics, and historical data of the last generation before actual production starts. This is briefly explained in **Figure 4** below:

Siemens also describes how a DTP can be used to enhance the efficiency of designing new products by virtually validating product performance and showing how the product is doing in the physical world and ensuring it meets the required expectations. They however refer to it as the Product Digital Twin. (SIEMENS, 2020)

Build/Manufacture Phase: Tao, et al.,(2018) discussed how the digital twin concept can be used in the manufacturing process by the fusion of the physical space and the information space to create what he referred to us Digital Twin Shop Floor (DTSF). This was aimed at improving resource allocation, production plan and process controls during the manufacturing process. The framework is based on of Physical Shop Floor (PS), Virtual Shop Floor (VS), Shop Floor Service System (SSS), and Shop Floor Digital Twin Data (SDTD). The convergence of SDTD, the three components of DTS (i.e., PS, VS, and SSS) interact with each other to realize the iterative optimization for resource management, production plan, and process control. This is briefly described in **figure 5**

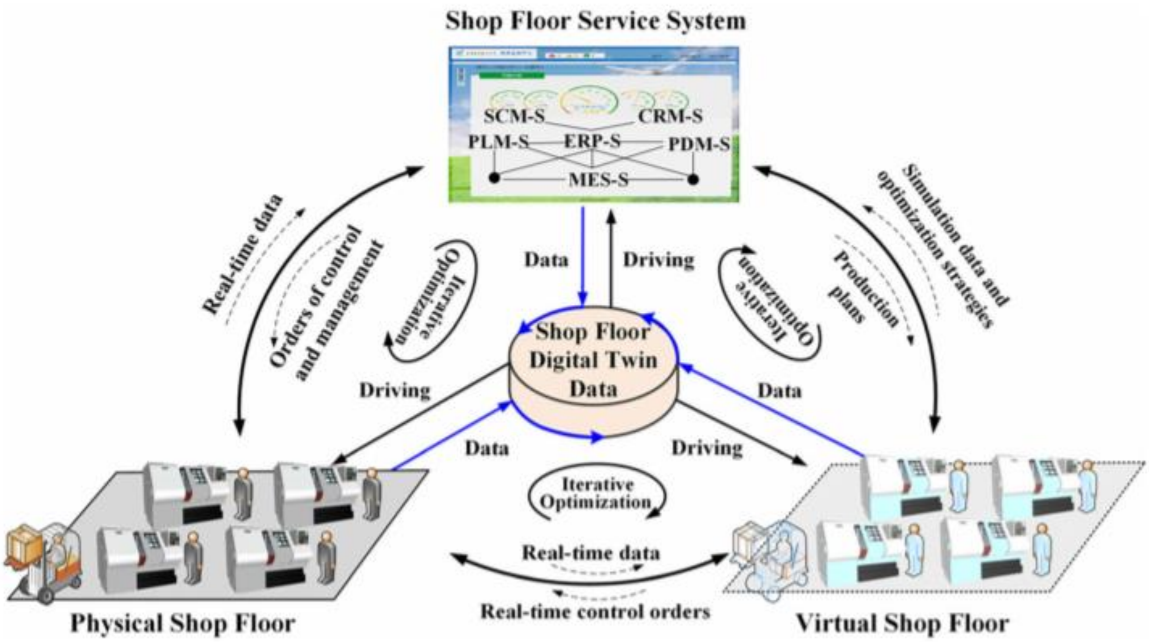

Figure 5: Framework for implementation of DT in manufacturing process as described by (Tao, et al., 2018)

Having a Digital Twin for production/manufacturing like the one described above will help validate how well a manufacturing process will work before productions/manufacturing starts. With the help of simulations, the most efficient production methodologies can be established to enhance productivity. Linking the data between the DTP or Digital Product Twin with the of the Digital Twin Shop Floor (DTSF) or Digital Production Twin can prevent costly downtime to equipment and predict when preventative maintenance will be necessary. This constant stream of accurate information enables manufacturing operations that are faster, more efficient, and more reliable. (SIEMENS, 2020) (Tao, et al., 2018).

Operational/Service Phase: This phase of the lifecycle is characterised by heterogeneous, complex structure and multiple layers of data representing the utilization and maintenance of the product and materials. Defects during this phase can lead to malfunctioning of the product or safety concerns and hence the need to regularly maintain products at this phase. (Tao, et al., 2018) described how the DT concept can be used to ensure that proactive maintenance/service of product using specific material, structural configuration and usage of a product as compared to the traditional approach which tend to be reactive and based on hearistic experience, worst case scenarios. (Tao, et al., 2018) proposed a framework based on realtime monitering with the help of advanced sensors and communication technologies providing data about energy consumption information, user operation and setting data , product running information , material structure information , parts wear information etc. The connection of realtime data and historic data allow the manufacturer to know the operational state of the product in realtime and also enables other services including energy consumption analysis and forecast, user management and behavior analysis, user operational guide, intelligent optimization and update, product failure analysis and prediction, product maintenance strategy and many more. This is briefly described in **figure 6**.

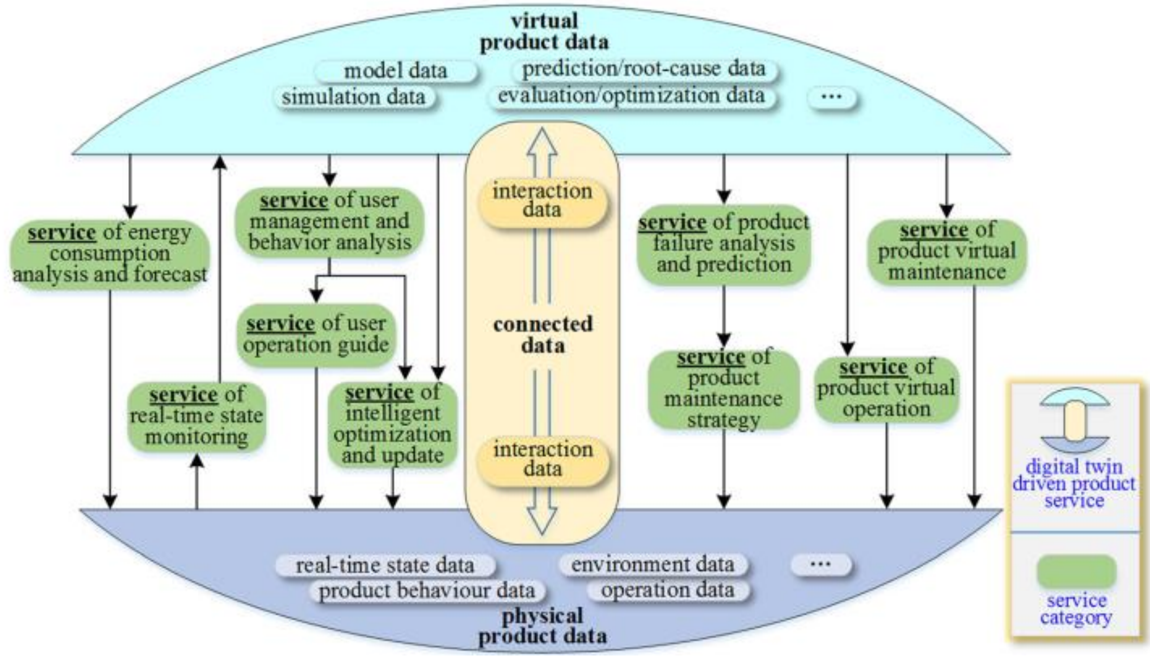

Figure 6: Digital twin concept to monitor operational phase as described by (Tao, et al., 2018)

(SIEMENS, 2020) describes the use of DT in the operational phase to capture data from products in operation and analysis to provide insight for informed decision making or improve on product and production system efficiency as a Performance Digital Twin.

To have a brief idea of the definitions of digital twins encountered during the literature review, please refer to **table 1**.

Source	Year	Definition
(Glaessgen & Stargel, 2012)	2012	*"The Digital Twin is an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin. The Digital Twin is ultra-realistic and may consider one or more important and interdependent vehicle systems"*
(Lee, et al., 2013)	2013	*"The coupled model is a digital twin of the real machine that operates in the cloud platform and simulates the health condition with an integrated knowledge from both data driven*

		analytical algorithms as well as other available physical knowledge"
(Rosen, et al., 2015)	2015	*"An autonomous system with very realistic models with the current state of processes and their behavior in reaction to their environment in the real world."*
(Schluse, et al., 2018)	2018	*"A virtual replica of a technical asset which contains models of its data (geometry, structure ...), functionality (data processing, behavior, ...) and its communication interface."*
(Canedo, 2016)	2016	*"It's the creating of a digital representation of a real-world object with the focus on the object itself."*
(Schroeder, et al., 2016)	2016	*"A virtual representation of a real product with the product information from beginning of life till disposal in the context of cyber physical systems."*

Table 1 Definitions of Digital twins encountered during research

The summary of the definitions shows that Digital twins exists in different variety across various industries, and they are defined according to purpose to which they are developed and also shows how the concept is evolving overtime.

It is essential to know that adoption of the DT concept has been widely successful in the manufacturing sector due to industry standards that guide the implementation of the concept. Some of these standards include.

ISO/CD 23247-1 (under development) – Digital Twin Manufacturing Framework Standard ISO/CD TR 24464 (under development) – Visualisation elements of Digital Twins IEC 62832:2016 – Technical specification of the Digital Factory Framework ISO/AWI 16400 – Equipment behaviour catalogues for virtual production systems

Main manufacturing data and exchange standards provided by ISO/TC 184/SC4

ISO/AWI 8000 – Data Quality Management and assessment standards for exchange

ISO 10303 STEP - Standard for the Exchange of 3D Product model data

ISO 10303-238 STEP-NC - Standard for the Exchange of 3D Product model data compliant Numerical Control

ISO 14649-1 to ISO 14649-121 – Standards providing data models for industrial automation systems and integration of physical device control for computerised numerical controllers ISO 15531 – Industrial manufacturing management data

ISO 15926 – Integration of life cycle data for process facilities

ISO/TS 18876-1 and 18876-2 – Integration of industrial data for exchange, access and sharing

ISO/DIS 23952 (under dev.) – Automation systems and integration – quality information framework (QIF)

IEC 62264 – International standard for enterprise control system integration

(Loscos, et al., 2019)

2.3 Industry 4.0 and its contribution to digital twin concept

As stated in the introduction, the fourth industrial revolution has also led to the adoption of the Digital Twin Concepts in many industries. Industrial revolutions are a result of significant technological advancement and the way people live. (Gunal, 2019) Whiles the first industrial revolution was triggered by inventions of machines powered by steam engines, the second revolution was triggered electricity and mass production of goods. In the AEC industry, the second industrial revolution was responsible for driving the industry in term of innovation in architectural design, beginning of computer aided design (CAD) and prefabrications among other things (Maskuriy, et al., 2019).

The third industrial revolution however was characterized by the use of electronics in production, and it involves complex deep transformations of systems, structures, institutes, relations, and technologies, which change the means, mechanisms, and content of people's organizing production, exchange, consumption, training, communication, and leisure. In the AEC industry this led to a new relationship between architects and technology impacting the production. Also, this led to the using diffused 3D computer-aided design software as a representational tool to improve precision and expand the limits of their creations by architects (Maskuriy, et al., 2019).

Industry 4.0 is a term introduced in Germany in 2011 that is defined 'as a new level of organization and control over the entire value chain of the life cycle of products, geared towards an increasing individualized customer requirements/satisfaction (Vaidya, et al., 2018)' (Gunal, 2019). According to (Gunal, 2019), Industry 4.0 was about revolutionizing the manufacturing industry by making machines they are connected and smart, and the main objectives was creating 'smart factories' and 'Cyber Physical Systems'. Industry 4.0 is powered by advanced technologies and concepts the includes, Digital Twins, IoT, robotics, big data analytics, cloud computing, systems integration, AR/VR, and simulation to enhance manufacturing and production by making it smarter, autonomous, cyber, and integrated. A couple of these concepts are briefly discussed.

Simulation: Simulations did not start with the fourth industrial revolution, it is however said to be the major empowering force behind Industry 4.0 because of the advancements of Computer Aided Design software's and 3D visualizations (Gunal, 2019). They are used as supportive tools to enhance decision making by following reflections gathered from various parameter changes and visualizations. Additionally, simulations are used to reflect what-if scenarios to improve the robustness of processes. In smart factories, virtual simulation enables the evaluation of autonomous planning rules in accordance with system robustness. (Ustundag & Cevikcan., 2018)

Cyber Physical Space (CPS*);* This is also another term this is constantly associated with Industry 4.0. It is used to describe systems in which natural and human made systems (physical space) are tightly integrated with computation, communication, and control systems (cyber space). (Vaidya, et al., 2018). In other words, it can be explained as supportive technology for the organization and coordination of networking systems between its physical infrastructure and computational capabilities. In this respect, physical and digital tools should be integrated and connected with other devices in order to achieve decentralized actions. (Ustundag & Cevikcan., 2018). Sensors and embedded systems are used to ensure high and precise coordination between the physical objects and computational services. (Kumar, et al., 2019). CPS focuses on the three (3) C's namely, **control, computing and communication** and does not require digital representation of the asset but rather it contains algorithms mainly for automation. (Loscos, et al., 2019)

Internet of Things (IoT); This is used to describe a digital environment where different resources and objects are embedded with actuators, digital devices, and sensors to enhance communication between each other and humans through the collection and exchange of data. The main purpose of IoT is to aid in object-to-object communication and sharing of data through the enhanced connectivity between physical objects, services, and systems. IoT environment has led to various industries in achieving automation for various purposes such as machining, heating, space lighting and remote monitoring. (Kumar, et al., 2019), (Gunal, 2019).

Other concepts associated with the fourth industrial revolution are robotics, big data analytic, cloud computing, AR and VR.

2.4 Digital Twin in the AEC industry

As seen from the previous chapter, the DT concept has been widely adopted in the manufacturing industry (automotive and aerospace sector) to help solve the problems related to PLM leading to higher productivity and efficiency in that industry. In order for the AEC industry to fully benefit from the digitization drive as a result of the fourth industrial revolution, it has to embrace or apply the concept of digital twins throughout the lifecycle of the built environment (Brilakis, et al., 2019). This chapter looks at efforts being made in the AEC industry about the Digital Twin Concept from BuildingSmart perspective, CDBB perspective and SPHERE (4-year, Horizon 2020 project that aims to provide a BIM-based Digital Twin Platform to optimise the building lifecycle, reduce costs, and improve energy efficiency in residential building).

2.4.1 BuildingSmarts Perspective

BuildingSmart which is the worldwide industrywide go to place for driving digital transformation in the built asset industry defines.

"*A digital twin (DT) - also referred to as digital shadow, digital replica or digital mirror - is a digital representation of a physical asset. Linked to each other, the physical and digital twin regularly exchange data throughout the PBOD (Plan Build Operate Decommission) lifecycle and use phase. Technology like AI, machine learning, sensors and IoT allow for dynamic data gathering and right-time data exchange to take place"* (Beetz, et al., 2020).

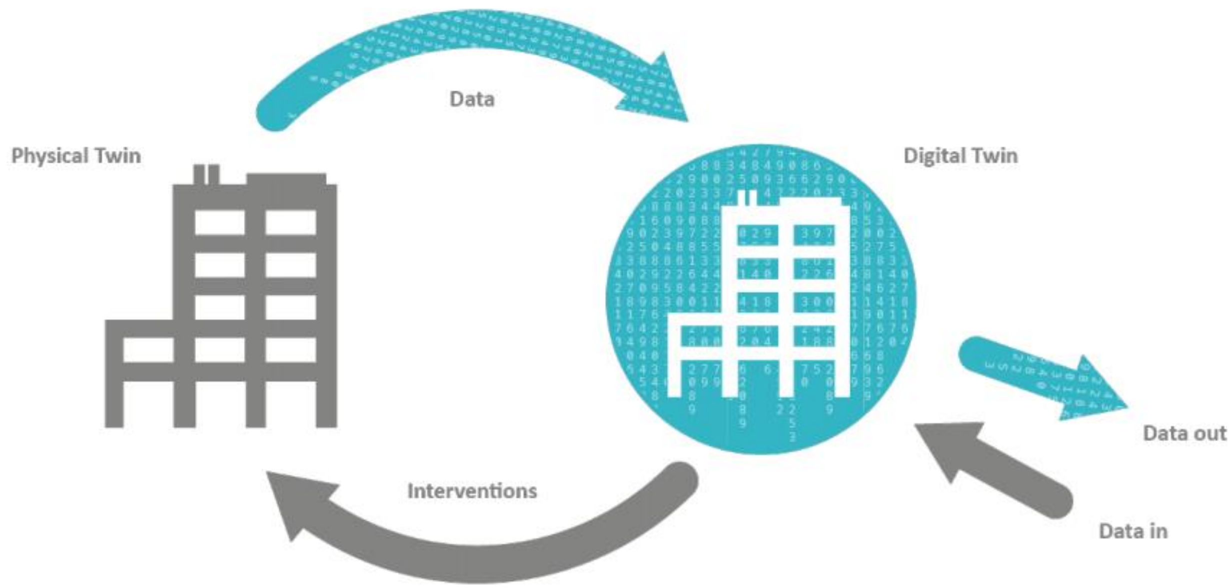

Figure 7 Definition of Digital Twin connected to Physical twin. Source: (Beetz, et al., 2020)

According to (Beetz, et al., 2020), adopting the DT concept has the potential to unlock economic, business, and environmental values in the built asset industry but recognizes the peculiar challenges that prevents the adoption of concept. The fragmented nature of the industry was the number one factor, while the lack of or underinvestment in IT infrastructure is also a stumbling block. According to (Beetz, et al., 2020) only 1% of revenues of firms are invested in IT. And considering the amount of investment need to fully implement the DT concept this is not enough. Notwithstanding however continuous adoption of BIM with its associated benefits coupled with population growth, climate change and pandemics has gradually drawing industry players to realize the potential the DT concepts brings.

Standardization is what has proven to make successful implementation of the DT concept in other industries and bSI recognizes the role all players including countries, cities, government authorities, asset owners, building project participants (designers, engineers and contractors), operators, standard setting bodies, and citizens must play in order to achieve the digital transformation. (Beetz, et al., 2020).

It is also essential to look at how the concept can be implemented the lifecycle of the built asset. (Beetz, et al., 2020), argues that it is essential to view the lifecycle as **PBO-I** because of its focus on USE as compared to the well-known plan-build-operate-decommission (PBOD), it also has a broader network focus of all connected systems encompassing infrastructure, built environment, social and economic, the natural environment as well as the citizens.

Figure 8 PBO-I concept of lifecycle Source (Beetz, et al., 2020)

A network of connected digital twins creates an ecosystem that combines/integrates dynamic data with static data from various sources to allow valuable, accurate and up to date insights forms the basis for informed decision making and increase in productivity and wellbeing. The benefits of the digital twin and the ecosystem in the entire PBO-I cycles is not limited to individual stake holder but rather includes players in the whole value chain including investors, owners, asset managers contractors, consultants, suppliers, tenants, or users. (Beetz, et al., 2020)

In order for the AEC the benefit from the implementation of the digital twin concepts. (Beetz, et al., 2020) listed the following as the way forward,

A wholistic view of the concepts where all components are part of a bigger connected system. This they said could be done through adoption of open and neutral forum where industry stakeholders and experts can discuss and develop holistic approach to address industry challenges and adopt open standard. This is where BuildingSmart(bSi) plays a big role in bringing together industry players and experts.

Anther limitation has to do with the information management in the bigger system to ensure interoperability. (Beetz, et al., 2020) mentioned three areas of focus namely, **standard of data model, standards for data management and integration and data security and privacy issues**.

2.4.2 CDBBs perspective for Digital Twins

The United Kingdom (UK) government in an effort to digitalize their economy has set out a clear vison and strong agenda to transform the delivery, operations and use of its built assets by harnessing the digital twin concept and its associated technologies have brought together all stake holders, including asset owners, mayors and leaders in the built environment to form an association called Centre for Digital Build Britain (CDBB). (CDBB, 2020) defines Digital Twins as; "*a realistic digital representation of an asset, system or process in the built or natural environment"*. They further differentiate between digital twins and any digital model as the connection it has with the physical twin and the ability to use this data unlock value by providing positive feedback into the physical twin. CDBB,(2020) further distinguishes between two types of DT as;

DT1 A dynamic model of an asset, with input of current performance data from the physical twin via live data flows from sensors; feedback into the physical twin via real-time control.

DT2 A static strategic planning model of a system, with input of long-term condition data from the physical twin via corporate systems; feedback into the physical twin via the capital investment process.

CDBB, in partnership with the University of Cambridge and the Department for Business, Energy and Industrial Strategy, manages the National Digital Twin program (NDTp) have been set up with three (3) main objectives.

The first objective is to enable a National Digital Twin, that refers to an ecosystem of Digital Twins, where the several DTs are connected to support better outcomes from the built environment. This serves as a national resource for improving the performance, quality of service and value of delivered assets, processes, and systems in the built environment. The second objective is to deliver an Information Management Framework to provide secure and flexible data sharing and also effective information management. The last objective is to create a Digital Framework Task Group, where people from government, academia, and industry come together to share insights, so they pull towards the same direction to facilitate the IMF.

Regarding enabling National Digital Twin, CDBB published the Gemini Principles to guide the NDT framework from developing and unto their use. The principles are made up of nine (9) values (9 main principles) which are to guide asset owners, mayors and leaders in the built environment in building of their own digital twins. Purpose, Trustworthiness, and function are the three (3) broad pillars the Gemini principles are based on and it is briefly explained in the **figure 9**.

Figure 9 The Gemini Principles Source: (CDBB, 2020)

Regarding the information management framework, its main purpose is to ensure or establish a common language by which digital twins of the built and natural environment can communicate securely and effectively. Since the basis of the DT is data captured from various source, the information management framework will lead to a more unified way of making sense out of the acquired data essential for getting more insights the systems or assets and ultimately lead to effective decision making that will positively impact on the wellbeing of the built environment. The information value chain showing the link between the diverse source of data and better decision making that lead to better outcomes is shown in **figure 10**.

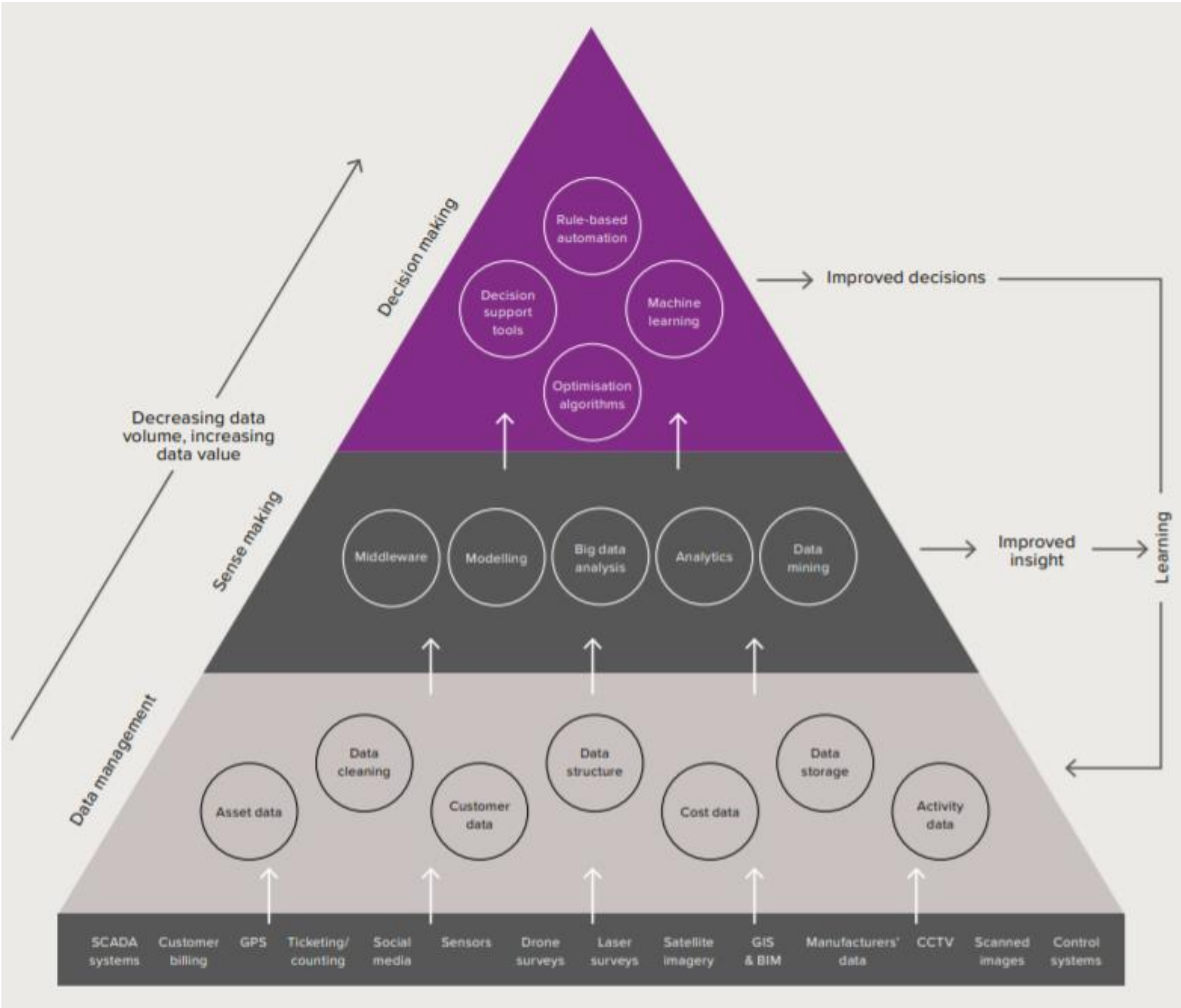

Figure 10 Information value chain Source: (CDBB, 2020)

According to (CDBB, 2020) ,DT can exist in the ecosystem in different varieties which include.

Variety of Purpose including future predictions and preventive maintenance routines, current state (intervention management, real-time status monitoring and control, diagnostics and prognostics to optimize performance and safety of assets) and history (learning from the past).

Variety of spatial space including asset or building scale, network or neighbourhood scale, system city or regional scale or national scale.

Variety of temporal scale meaning it can be used at any point in the lifecycle of assets, systems and processes and it can be static or dynamic. It can be used to address different temporal scales including operational timescale, reactive maintenance timescale, capital investment timescale and planned maintenance timescale.

Variety of approaches to modelling including geometric and geospatial modelling, computational/mathematical or numerical modelling and Artificial Intelligence and machine learning.

The main purpose of the **Digital Framework Task Group (DFTG**) is to guide the co-development of IMF and connect all stakeholders who are developing digital twins.

(Loscos, et al., 2019) related the definition of the types of DT as defined by (Grieves & Vickers, 2016) relating to DTP, DTI, DTA and DTE to what pertains in the AEC sector.

Building Digital Twin Prototype (BDTP); This is used to describe an asset during design and construction containing information that is necessary to describe and produce a physical version that duplicates or twins the virtual one. The information includes.

- Employer requirements included inside contracts, previous legal and geotechnical information of the land.
- Information model in the form of an Object type DB which includes 3D geometric information as well as materials and elements inventory
- Bill of processes as comprehensive log of past processes and actors based on minutes and confirmed communication.
- Bill of Services as the current evolution on the functional characteristics of the asset, starting back from initial employer requirement
- Bill of disposal (e.g. material passports, selected deconstruction techniques)

Building Digital Twin Instant (BDTI): This refers to a DT that is linked throughout the life of a specific corresponding physical product, including pairing when the asset start operation. This is similar to an AS Built documentation and it includes but not limited to the following:

- A full information model including 3D model with General Dimension and Tolerances that describes the geometry of the physical instance and its components.
- Bill of Materials that lists current and previous elements and component (architectural, structural, and building services)
- Bill of process that lists the operations that were performed in creating this physical instance along with the results of any measurement and tests on the instance (eg cloud point surveys of inner services, structural load test,…)
- Service record that describes past services performed and components replaced (major/minor retrofitting and regular upkeeping)
- Operational states captured from actual sensor data, current, past actual and future predicted (BMS, SCADA/IOT sensors, Facility Management Servers, simulations)

Building Digital Twin Aggregate (BDTA); As in the manufacturing sector, this represents the aggregation of multiple DTI's. They don't have and independent data structure but rather are a computing construct which provide access to all DTI's, hence allowing ad-hoc and proactive queries for benchmarking and comparisons.

Building Digital Twin Environment (BDTE)*:* This serves two (2) main purposes which are Predictive (intimately linked with simulation tools of DTP and DTI), and Interrogative (applying DTI and DTA for in-depth analysis).

2.4.3 Maturity levels

It is essential to focus on the purpose of DT and understand the benefits of the different milestones and realize in what ways value grow by maturity. (Evans, et al., 2019) proposed an industry-agnostic maturity spectrum, which identifies various elements and offers a framework for communication of the progress demonstrated in Figure 11. While the digital twin is under development, every element will increase its complexity and connectivity and value. It is fundamental to identify clearly, realize, and justify the increased complexity and connectivity's objective and value what depends on efficient application and management. (Evans, et al., 2019)

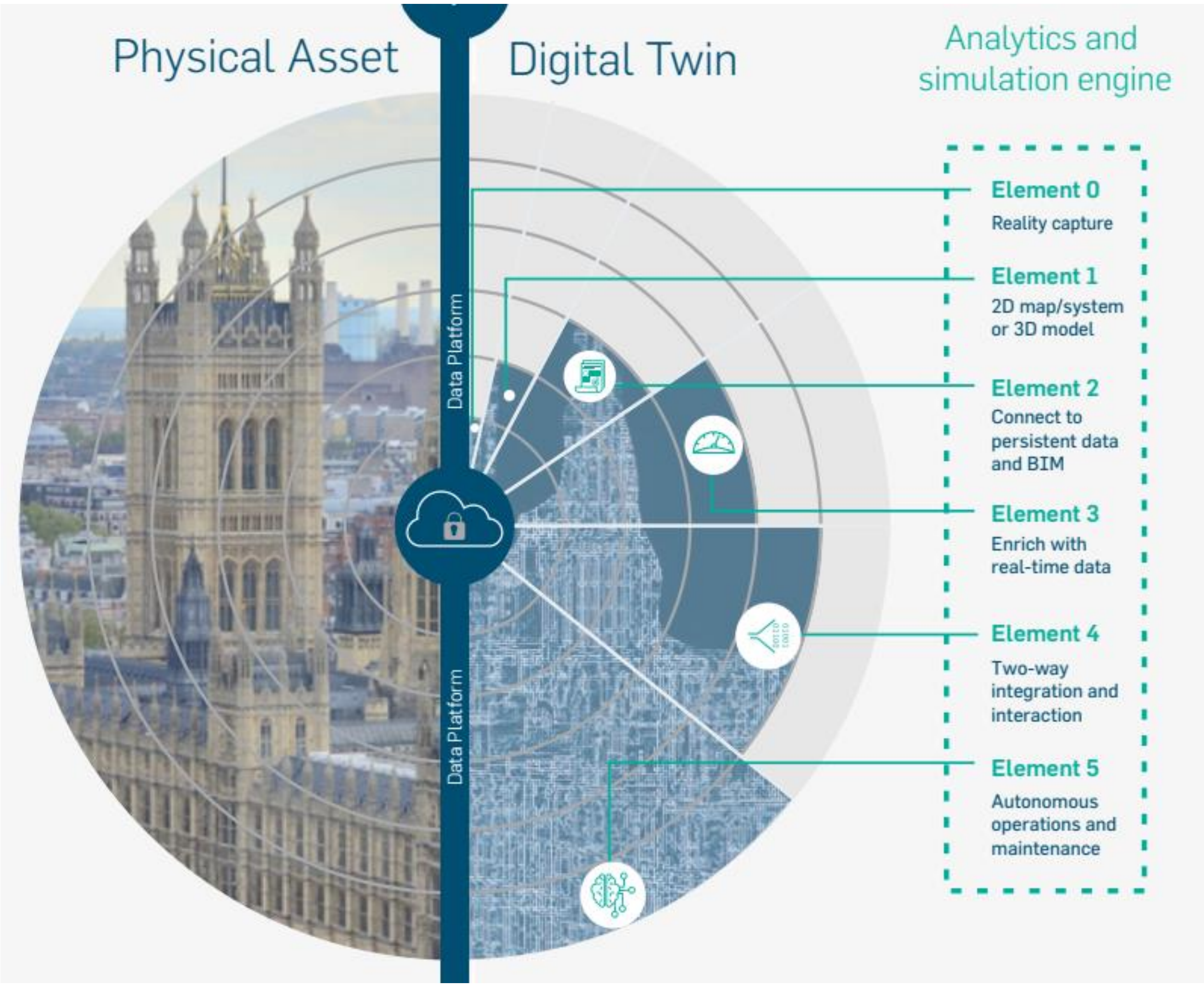

Figure 11 Maturity Levels of Digital Twins Source (Evans, et al., 2019)

There are 6 maturity levels. The implementation of the maturity level elements is not significantly linear or sequential, for the reason that a twin could have features of higher and more complex elements before lower elements. The maturity levels go from Element 0 to Element 5. (Evans, et al., 2019)

- Element 0

This element is only relevant in the case of an existing physical asset. The first element in creating a DT is to have an adequate, as-built data set of the asset. Element 0 is the essential element where data is connected and overlaid. This element provides value in having spatial context, better asset certainty and understanding. The data is gathered through different surveys, and reality capture approaches, such as point cloud scanning, photogrammetry, drawings, sketches, etc., are more specific, effective, and cost less than a few years ago, together with costing more than conventional survey methods. This element provides value by having better asset inevitability, understanding and spatial context, for instance, in areas where a large distribution of assets are built and ageing. (Evans, et al., 2019).

- Element 1

This element is the usual starting point for a new asset since it is the product of the design process; it can also be updated via reality capture after the construction phase to create an as-built model. The models are object-based, without containing metadata or any BIM information. It converts the point-cloud from Element 0 into a 3D model or an object-based 2D map/systems. Today the conversion is a manual process, nevertheless soon this process will be semi-automated, including machine learning. At this level, the twin gives significant value through design or asset coordination and optimization. (Evans, et al., 2019)

- Element 2

More benefits are recognized when Element 1 is connected to datasets, for instance, asset management information, design information, material specifications and later enhanced with metadata. The data is collected from existing systems, not stored in the 2D or 3D model. This gives the foundation of project planning, engineering, operation. It makes a single reference point where all data can be seen and analyzed. It allows faster decision making and better collaboration. At this maturity level, a data model supports running various simulations against the asset directly in the twin or via connected simulation applications. (Evans, et al., 2019)

- Element 3

At this maturity level, dynamic and operational data from the physical asset to the digital asset is collected in real-time through a one-directional flow and conducted by sensors, connected devices and the Internet of Things (IoT). The analysis of data can help to predict the behaviour of the asset and help decision-making, including feeding back the results to update the information in the existing system. Element 3 could be identified as the starting point of a 'real' DT, nevertheless reaching this level involves earlier steps which are usually not described. (Evans, et al., 2019)

- Element 4

The condition of the physical asset can be modified through the DT by feeding back the results of the analysis and updated into the twin. For instance, a physical valve could be manipulated via the initiation of the action from the twin. The integration at this level needs mechanical augmentation and additional sensor of the physical twin. This integration can be applied among the twin and other DTs. For instance, immersive technology can be used to modify the design by a designer; the modification is pushed to the applications that are connected to the twin. The connected applications calculate the impact of the modification and update the geometry and data according to it. These modifications and their impact will reflect in real-time into the twin, and the designer will be able to see it. This integration shows human-to-machine and machine-to-machine interaction with DTs. (Evans, et al., 2019)

- Element 5

This level of maturity is simply aspirational at the moment. However, DTs have the potential to learn and evolve to be a source of institutional knowledge and gain valuable experience about the behaviour of the physical twin so that it could be completely autonomous. The full consequence of this level of maturity and the valuable benefits what it will provide are yet to be explored. (Evans, et al., 2019)

2.5 Comparison of Building Information Modelling and Digital Twin

Digital Twin concept involves the digital transformation of how an organization operates and involves changing the mindset of the people in an organization to be successful. (Bart Brink, 2020). Building Information Modelling (BIM) cannot be ignored when digitization in the AEC industry is being discussed. Digital twin concept is not a technology but instead relies on a series of other technologies in order to realize its potential. A Building Information model representing a 3D model rich with semantic information serves as a database for all assets and facilitates exchanges of information between stakeholders in a unified and standardized way (Pauwells & Petrova, 2018). During the operation and maintenance phase, it can also be used as a repository or source of information that supports various activities of existing buildings (Lu, et al., 2020)**.** However, during the O&M phase of a building, the lack of integration and application of BIM (Lu, et al., 2020) summarized as due to three main reasons, namely Technology-related issues. Information Related Issues and Organizational Related issues. There is a lack of awareness of the benefits of BIM in operation and maintenance phases (Shalabi & Turkan, 2017). This partly due to the lack of clear and validated benefits of BIM in facility management practices, lack of integration between BIM and IoT due to problems associated with legacy formats that are not aligned (Boje, et al., 2020) and technological issues in integrating BIM and IoT to monitor assets during operation and maintenance (Becerik-Gerber, et al., 2012). Another reason for this may be partly due to the multifaceted, complex challenges of asset management and the asset management frame's alignment to the BIM information management processes (Lu, et al., 2020).

However current BIM implementation and adoption according to the BIM wedge as shown in Figure 12 below, in developed countries like UK, Denmark, Norway etc. can be said to be at maturity level 2 with a few countries pushing towards the achievement of BIM maturity level 3.

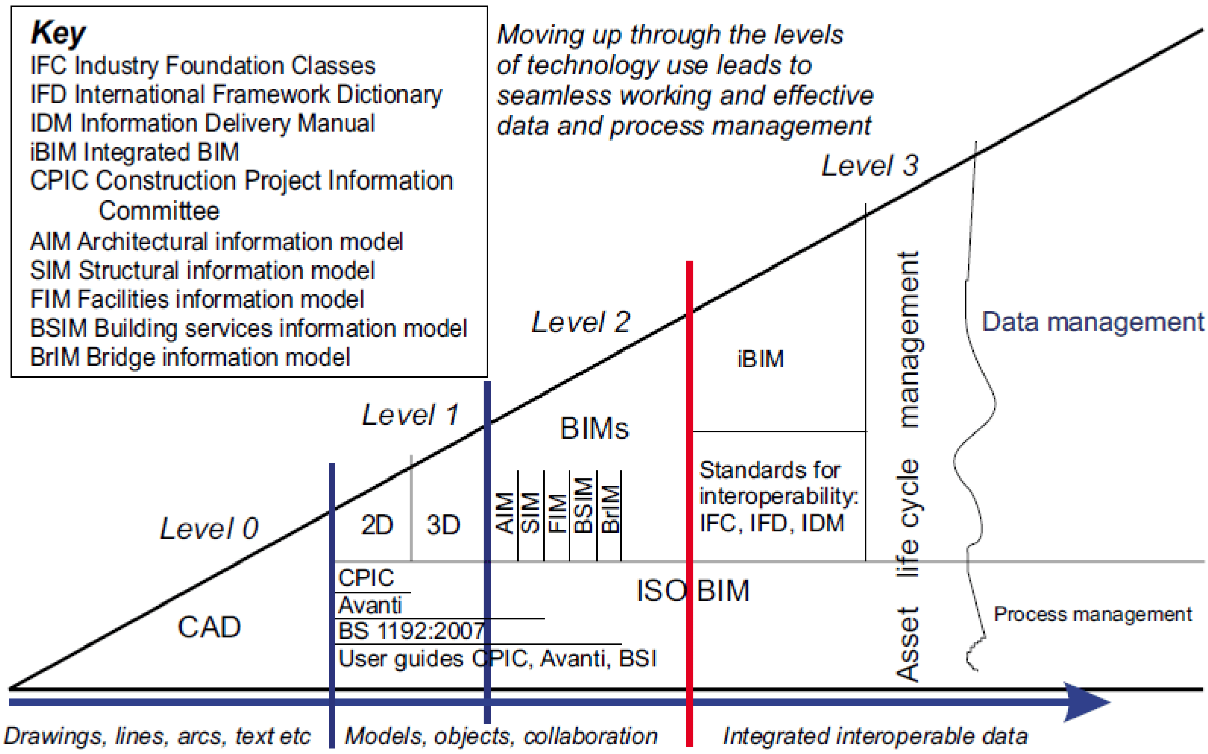

Figure 12 BIM Wedge Source: Brew Richards 2008

CDBB proposes in order to achieve an integrated and interoperable system that enhances O&M procedures like system portfolios, service delivery processes, user information and social systems as envisaged in BIM level 3 and 4. It is necessary to adopt the concept of DT which relies on the integration and interfacing of BIM data to services delivery processes, in a secure information landscape and across a federated DT (CDBB, 2018) as BIM processes alone cannot achieve this. So, a DT is relatively much broader from the information richness and analytical capabilities perspective than BIM. DT can be implemented for predictive maintenance during building operation (Qi & Tao, 2018) as well as for enhancing building operation (Khajavi, et al., 2019). It could provide valuable input for designing future buildings based on identified issues as well as for improvement areas that are revealed throughout the use of the building (Khajavi, et al., 2019). It could also be beneficial for improving resource efficiency, enhancing the comfort of the tenants, analysing what-if scenarios to optimize the design of the building (Qi, et al., 2018).

As stated earlier, BIM is likely to reduce the amount of time taken for updating databases during the Operation and Maintenance phases of a built asset by 98% (Lu, et al., 2020). There also exist some similarities in BIM processes and DT concept. **They seek to enhance visibility, align stakeholders, support planning and ultimately enable stakeholders to view the project**

through its entire life cycle and not as a siloed capex investment asset (Bart Brink, 2020)**.** BIM processes and framework establishes clear project vision and supports business outcomes before actual design starts and construction follows. BIM processes and tools also provide an efficient way in managing construction logistics, clash detection, site monitoring, quality management, site monitoring, construction simulation visual communication and scheduling (Boje, et al., 2020), but DT is beneficial when there is a need to continuously improve and adapt projects to deliver more excellent value to stakeholders using real-time insight (Bart Brink, 2020). As stated earlier, BIM is likely to reduce the amount of time taken for updating databases during the Operation and Maintenance phases of a built asset by 98% (Lu, et al., 2020) and forms the basis for developing a digital twin. Information regarding the project, assets, organization are already agreed on according to ISO 19650, ISO 55000, and ISO 9001 and fits in developing a DT, as shown in Figure 13.

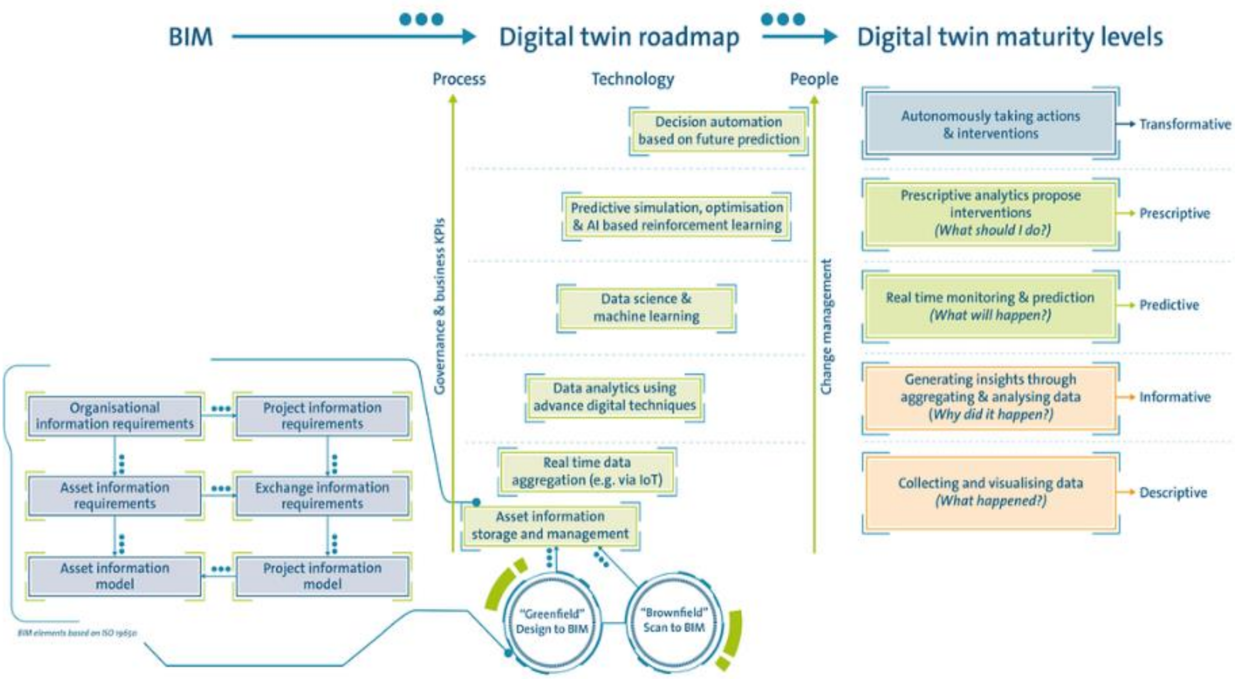

Figure 13 Relationship between BIM and Digital Twins Source: (Bart Brink, 2020)

The adoption/practice of BIM according to ISO 19650 is about getting benefit through better specification and delivery of just the right amount of information concerning the design, construction, operation and maintenance of buildings and infrastructure, using appropriate technologies. This has led to.

- 'Clear definitions for the information needed by the project client or asset owner, and for the standards, methods, processes, deadlines and protocols that will govern its production and review.

- The quantity and quality of information produced being just sufficient to satisfy the defined information needs, whilst not compromising health and safety or security. Too much information represents wasted effort by the supply chain and too little means clients/owners take uninformed decisions about their projects/assets.

- Efficient and effective transfer of information between those involved in each part of the life cycle – particularly within projects and between project delivery and asset operation.

- *Informed and timely decision making*.' (UKBIMAlliance, et al., 2019)

According to (Camposano, et al., 2021), DT could be an efficient solution to link the information gaps between the BIM models and the information systems that are used during the Operation and Maintenance phase. They come to a conclusion that difference between BIM and DT can be associated to objective and subjective reasons. Both concepts have similar attributes, and DT mostly described with greater complexity. They consider the question, from a theoretical point of view, if DT refers to a completely different product than the current one, which is defined as a digital model, from the objective point of view and not just from the subjective. Based on the key attributes of built asset models and DT that (Camposano, et al., 2021) defined according to FM practitioners, the propose that DT is composite enough, so it could have its own definition, on the other hand, it has various features that are common with CAD or BIM models. (Camposano, et al., 2021)

Finally, (Loscos, et al., 2019) combined the current state of the art processes and benefits of BIM practices and standards and defined the contents of BIM based Digital twins as follows;

BIM based Digital Twin Prototype (BDTP): During the design and construction phase the adaptation of ISO 19650-1:2018 has provided the basis for a BIM based Digital Twin Prototype. It contains but not limited to Project Information Model (PIM), BIM Executing Plan (BEP), standards, data properties, scope of all internal and external requirements (Project Information Requirements (PIR), Organisational Information Requirements (OIR) and Asset Information Requirements (AIR)), previous files related to the setting, including terrain legal information (e.g. Cadastre, Historical…) as well as its geometrical information (topological surveys, geotechnical campaigns…). It can also include non-structured data related to the mode. Relevant information from other databases which are updated managed dynamically must be linked to the PIM in other to achieve the BIM based Digital Twin Prototype. (Loscos, et al., 2019) highlighted that linking the outside databases to the PIM is a major limitation in achieving the BDTP and needed to be addressed.

BIM based Digital Twin Instance (BDTI): This has to integrate all the information stored in the BDTP above and includes sequentially use of past information model to structure this type of DT**.** Under BIM standards ISO 19650-1:2018 a new asset entering into the operations and maintenance phase may include the evolution of AIM starting from previous AS BUILT model of information. The initial AIM provides information of the current instance including the General Dimensioning and Tolerances (GD&T). Bill of Material and the Bill of representative processes (BEP and BCF communications) , along with the results of any measurements and tests on the instance(cloud point surveys of inner services, structural load tests , Geo-radars), service record describing services performed and components replaced(retrofitting), and operational states captured by actual sensor data , current, past actual and future predicted(BMS, SCADA/IoT sensors, Facility Management services, simulation). All these data or information must be linked dynamically to the BIM models of which AIM is part.

BIM based Digital Twin Aggregate: This involves the collection or synchronization of multiple digital twin instances. this presents the most difficulty in the because it involves the computational construct of the synchronisation of heterogenous digital twins. Standardised libraries can help homogenise the whole aggregation of information. ISO-19650, provides the basis to develop specifications using AIR to manage future BDTA because it implies a set of standardised definitions of the models object used in the AIM's. , (Loscos, et al., 2019) propose a platform as a service architecture to help achieve this and it includes services such as *Linked data semantic ontology, Integrated IoT platform, IFC reader, Blockchain, digital twin libraries*.

BIM bases Digital Twin Environment: The BDTE will be able to expand any current CDE functionalities to be able to manage all the PIM and AIM information dynamically, plus the connection with the on-site monitoring devices and actuators, especially for the asset operational stage. (Loscos, et al., 2019)

3 Methodology

This chapter gives an overview and description of the different methods and approaches chosen to collect data and information relevant to the thesis.

3.1 Research Design

The main aim of the research design is to plan the thesis to highlight what is relevant to the problem statement in order to collect the relevant data. Research designs are unique to every thesis. Hence, the research design is an exploratory or descriptive research design since it provides the opportunity to describe the issue under the research topic and gather analysis and present the data collected. It also includes the evaluation of the solution provided. This is achieved with the help of a systematic literature review as wells as a collection of interviews (primary data collection) conducted with various stakeholders involved in the operation and maintenance phase to understand the level of technologies they use in their daily operations.

An inductive approach is used to analyse the data received from the interviews and literature review to understand the concept of digital twins and the level of implementation of associated technologies as well as the benefits they provide to the various stakeholders. The research process will be completed by analysing emerging patterns from the data collected through the literature review and interviews.

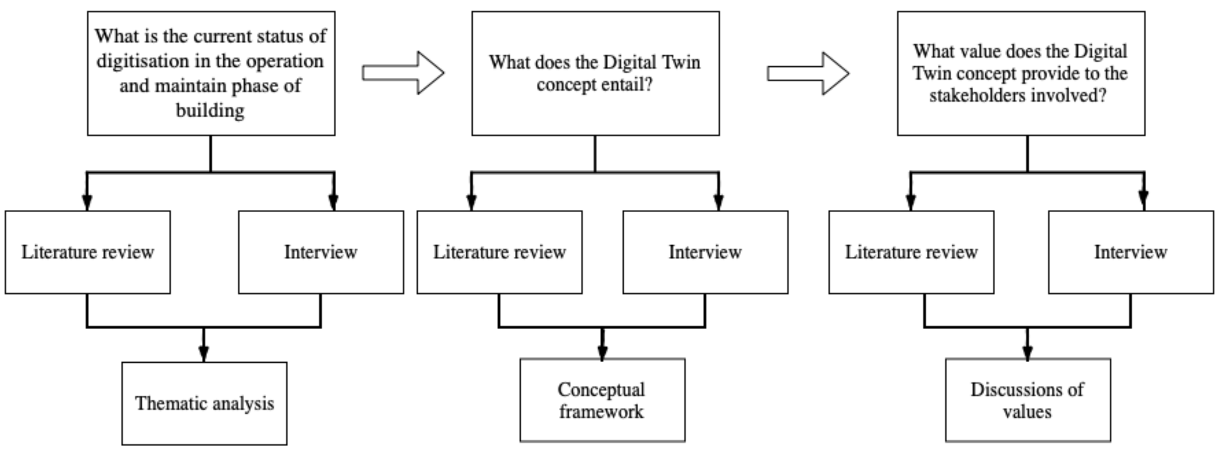

Figure 14 Research Design

3.2 Data Collection

Data collection is a critical component of every research paper and so it must be done in a well structure way. This study involved both a systematic literature review and conducting of interviews as data collection methods and these a briefly discussed subsequently.

3.2.1 Literature Review

In order to identify critical literature for the research, a systematic literature review was carried out using the Prisma flow diagram to highlight the shortlisted articles.

3.2.1.1 PRISMA

The PRISMA method was adopted because of its ability to help in transparently reporting systematic literature reviews (Moherl, et al., 2011). This method is the combination of evidence-based set of templates, namely PRISMA check list and PRISMA flow diagram. The checklist is broken down into 7 different topics with sufficient checklist elements. The goal of the checklist is to help the authors towards critical analysis of selected research papers. To choose the significant research papers, the PRISMA flow diagram is intended to be used as the subsequent step. The diagram consists of 4 stages:

- Identification: in this step the relevant databases for research are selected. Key words for the research are also defined. Proceeding on the duplicates found in different databases are excluded.
- Screening: at this stage, the research papers are assessed depending on the title and later on the abstract, as well as the introduction and conclusion.
- Eligibility: In this step the research papers are assesses by full text.
- Included studies: in this step the authors decide, based on the assessment, how many of the research papers will be included in the literature review.

The PRISMA method is supplemented with the snowballing method, to identify the last set of research papers.

3.2.1.2 Snowballing

The literature review was carried out to help acquire knowledge from existing research carried out on the subject matter and identify research gaps that will help guide the writing of the report. A traditional or narrative literature review was carried to acquire a comprehensive background to understand current knowledge and highlight the significance of new research (Cronin, et al., 2008). This was done to gain some theoretical, empirical, and methodical knowledge within the subject area. Some of the literature looked at a couple of systemic reviews carried out in the subject area. These systematic review papers were relied on as a source of qualitative data integrated into the report as and when the need arises. The review was written as Literature Review, meaning emphasis was put on the most recent research on the subject area with ten years' limitations. The resulting research papers, books, conference papers were chosen and assessed for relevance with emphasis was given to peer-reviewed articles.

Furthermore, the snowballing method (Figure 15) was chosen to perform a structured literature review. The snowballing method is based on using the reference list of a paper in order to find additional articles. Nonetheless, snowballing is beneficial not just for using the reference list of a chosen paper, but to supplement it by a methodical way of review to see where the different papers are cited and referenced. (Wohlin, 2014) . Backward and forward snowballing implies the use of references and citations respectively. In the snowballing method, there are 2 steps, Start set and iterations.

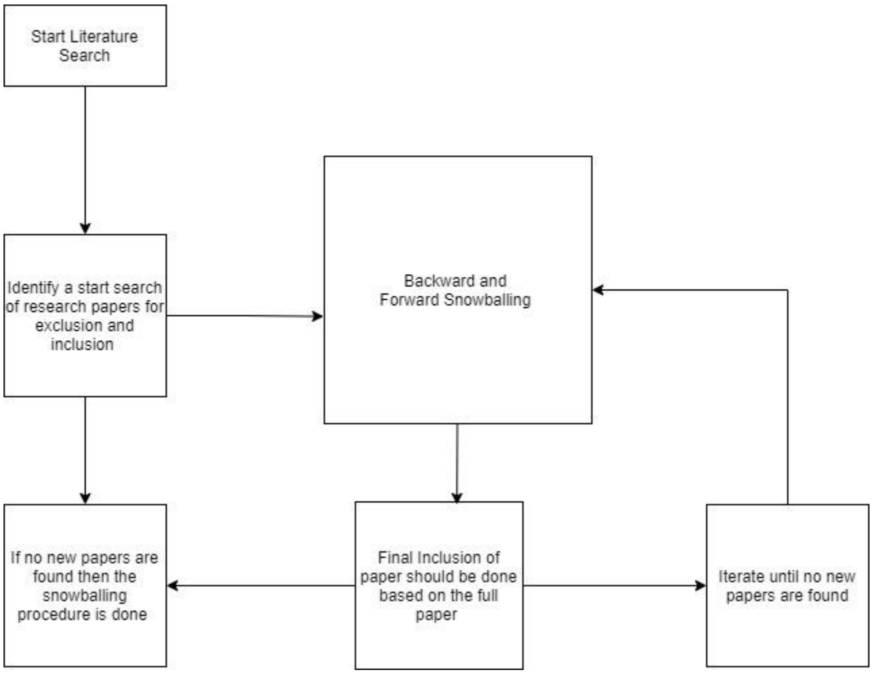

Figure 15: Snowballing method adopted for report Source: (Wohlin, 2014)

3.2.2 Interviews

The second part of collecting data in this thesis was executed by conducting "three" interviews with the relevant stakeholders within the scope of the topic of operation and maintenance phase of the building's life cycle to better understand the stakeholders' point of view regarding the researched problem. More precisely, this includes identifying relevant stakeholders, and better understanding the current state of digitization of the operation and maintenance procedures in the AEC industry in addition to the literature review.

The interviews have been executed as semi structured interviews, meaning that several questions were developed as open and exploratory questions to gather qualitative data from the stakeholders as well as leaving place for additional follow up questions in order to get a better insight of the interviewees point of view. The purpose of the interviews is to help the writers to gain knowledge about the status of digitization in the operation and maintenance phase of a building as well as to provide information to be able to develop a conceptual framework for implementing the Digital Twin concept to improve building operation. The main conclusions from each interview are very similar and helped strengthen the core idea of this research paper. These can be found attached to this paper in the *Appendix* chapter.

3.3 Data Analysis

Data analysis will bring us closer to the answer which is the solution!

Thematic Analysis is chosen in this thesis to analyse the qualitative data provided by the interviews. Thematic Analysis is used for qualitative content analysis, where common themes or topics, patterns of meaning come up repeatedly and differences are identified in qualitative data; for instance, in interviews; in order to gather descriptive as well as explanatory outcomes due to themes i.e., group of data. (Caulfield, 2021)

Its main characteristic is the matrix output: rows i.e. cases such as interviews, columns i.e. codes and cells of data, contributing to be able to systematically structure and analyse collected data from the interviews. The fundamentals of the qualitative analysis are comparing the data. The capacity to compare data across cases and/or amongst individual cases is part of the process and structure of thematic analysis. Thematic analysis presents stringent steps to lead towards eminently structured and summarized data. Even though the different interviewees might have different points of view or experiences regarding the topic, this is no issue as the aim after all possible to compare.

Thematic analysis is a flexible tool that can be integrated with several qualitative approaches where the goal is to create themes. Developing the themes is a relatively often seen element of qualitative data analysis, including systematic investigation to find patterns in order of developing complete descriptions that draws attention to the problem under research (Caulfield, 2021)

In this thesis a combined approach of deductive and inductive approach is appropriate as the project has explicit problems to research, nevertheless planning to leave space to explore unforeseen views of the interviewees' experience. For instance, new insights from the interviewees might propose hidden enquiry, where close analysis could expose divergence in the data, as a result, it requires follow up exploration.

Thematic Analysis done for this paper has 7 steps:

1. Transcription: In this step the interviews are transcribed word for word focusing on the content, meaning that the irrelevant part that has no value for the research can be left out.

2. Familiarization with the interview: in this step, after transcribing the interview, it is important to be familiar with the interview by using both the interview recordings and the transcripts; as well as any reflective notes which were taken during the interview as it could be useful later during the further steps.

3. Coding: During this step, the transcript is read line by line and labelled with paraphrases which explains the interpretation in the paragraph referring to its importance. The goal of coding is to classify the data so systematically comparison can take place with other data set i.e. other interviews.

4. Generating Themes: In this step the codes from the previous step are categorized into clearly defined themes. The themes are generally broader than the codes.

5. Reviewing Themes: it includes ensuring that the themes are necessary and accurate from the data and helps in the research.

6. Defining and naming themes.
7. Writing Up

4 Systematic Review of Application of Digital Twin in Building Operation and Maintenance

This chapter helps in answering first the problem formulation.

How can digital building twin concept add value to the various stakeholders during the operation and maintenance phase of the lifecycle of the building?

- What is the status of digitization in the operation and maintenance phase of building?
- What does the digital twin concept entail?
- What value can it provide to the various stakeholders involved?

The chapter is divided into segments that attempts to proffer an answer to the research question.

This section reviews the literature on the application of Digital Twin concept in real life and identifies the enabling technologies been used in the application of DT, the stakeholders involved and the end users as well as benefits gained. The review is done in the form of a thematic analysis of research content. The review was conducted following the PRISMA framework utilising the AAU library database with keyword search, using a range of strings and intermediary keywords such as OR X OR, AND, Asterix, concerning the following keywords '*Digital Twins in AEC', 'BIM, IOT* and *Digital Twins'*, '*Digital twins and Operation and Maintenance'*, '*BIM and Digital Twins'*, 'Building Operation and Digital Twins' ,The search resulted in 154 hits which were screened for duplicates (24) and the screened according to titles and abstracts and also according to year of publication (2018) leading to 20 hits . A total of 11 studies were chosen for qualitative analysis/thematic analysis at the end of a thorough read through.

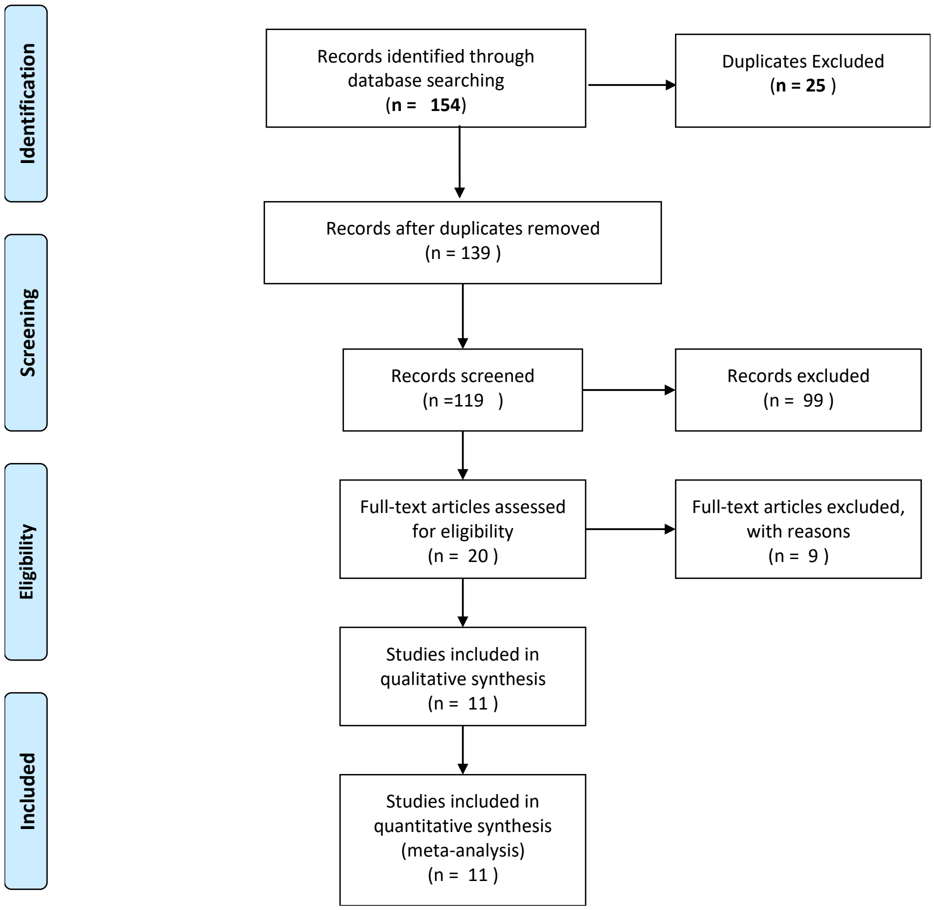

Figure 16 PRISMA framework diagram showing paper selection process

4.1 Literature Analysis

After performing the initial screening of the literature and reading thoroughly through the selected articles, the themes run across the chosen articles and will enable answering of the problem formulation. The themes are described in **Table 2** as follows,

Authors	**Need for DT /Descriptive Codes/Factors Identified**	**Emerging Themes**
(Lu, et al., 2020)	To detect anomalies in the daily operation and maintenance it requires cross referring of multiple data sources for building facility information like CMMS, BAS, IWMS etc. Hence DT concept to integrate multiple data source and enhance data availability	***Smart Buildings***
(Peng, et al., 2020)	There are about twenty (20) different systems used for dynamic data sources, the need for a more intelligent and integrated platform that can enhance the operations of the hospital. Hence DT	
(La Russa & Santagati, 2020)	The need to innovative methods to allow advanced management of museum's collections, hosted in historical buildings through the development of DSS to implement effective conservative strategies	
(Lu, et al., 2019)	The need for an effective and intelligent asset management system to maintain dynamic data and support various activities whiles contributing to a comfortable environment	
(Xie, et al., 2020)		
(Heaton & K.Parlikad., 2020)	Development of Asset Information Model to support the establishing of DT	
(Lu, Xie, Parlikad, Schooling, & Konstantinou , 2020)	Smart Building	
(Lin & Cheung, 2020)	Smart Cities	***Smart Cities***
(White, et al., 2021)	The need for citizens to contribute to policy and planning decisions. By making DT available on the internet where citizens can give feedback.	
(Küsel, 2020)	The need agile systems that can deliver quick and real time into as built assets to all stakeholders.	
(Lu, et al., 2020)	Smart Cities	
(Austin, Delgoshaei, Coelho, & Heidarinejad, 2020)	Need to improve urban performance and identify trends and spatiotemporal pattern in city behaviours	

People Involved in Developing DT		
(Küsel, 2020)	Property owner, architectural design team, facilities manager, a maintenance manager, a MEP Manager	***Identification of stakeholders/End users***
(Lu, et al., 2020)	Estate Management Team, Facility Management team, Consultants	
(Peng, et al., 2020)	General Contractors DT Consulting Team, DT management Team, Hospital Managements	
(White, et al., 2021)	Software Developers, Citizens, Urban/City Planners	
(Lin & Cheung, 2020)	City Planner and Building Operators	
(La Russa & Santagati, 2020)	Facility Managers, Maintenance Manager, MEP manager, Software Developers	
(Lu, et al., 2019)	Asset Managers, Facility Managers, Software Developers	
(Xie, et al., 2020)	Facility Managers, Maintenance (Site) Worker, Software Developers	
(Heaton & K.Parlikad., 2020)	Asset Managers	
(Khajavi, Motlagh, Jaribion, Werner, & Holmstrom, 2019)	Building Operators (MEP), Software Developers	
(Lu, Xie, Parlikad, Schooling, & Konstantinou, 2020)	Asset Managers and Building Users	
(Lu, et al., 2020)	Estate Management Team, Facility Management team, Consultants	
Processes and tools used in development of DT		
(Küsel, 2020)	MBSE, BIM, AIM, IoT, GIS information, BMS, Portfolio Managements System, Maintenance Ticketing System, Communication Logging System, Tenant Management database	***Enabling Technologies***
(Lu, et al., 2020)	As-is BIM model, WSN enabled IoT, RFID, Cloud Computing, ETL, Autodesk Forge API, AWS DynamoDB, web-based program (.Net) using C# and JavaScript	

(Peng, et al., 2020)	3D Point Cloud, 3D BIM, Big Data Analytics, Cloud Storage, Continuous Life Cycle Integration, ETL, Mixed Reality	
(White, et al., 2021)	Stereoscopic or aerial photography to 3D (FBX), IoT, Unity Gaming, OpenStreetMap, SUMO	
(Lin & Cheung, 2020)	BIM (Autodesk Revit- Navisworks), WSN enabled IoT, C#.NET microframework, Navisworks API, Cloud Computing	
(La Russa & Santagati, 2020)	3D Point Cloud to BIM (laser scanners, photogrammetry, terrestrial laser scanning (TLS), Surface from Motion), VPL (Dragon Fly, honeybee, Grasshopper), Machine Learning algorithms (Linear regression) , WSN enabled IoT	
(Lu, et al., 2019)	3D BIM (extended ifc format), WSN enabled IoT, BMS, AMS, SMS, Cloud computing (AWS),ETL	
(Xie, et al., 2020)	AR, BIM, BMS, WSN IoT, Cloud Computing (AWS), Machine Learning Algorithms (CUSUM, Moving Average, binary segmentation change point system)	
(Heaton & K.Parlikad., 2020)	Point cloud to BIM, 3D BIM (REVIT-ifc), AIM classification systems (UNIclass), ETL, Relational Database	
(Khajavi, Motlagh, Jaribion, Werner, & Holmstrom, 2019)	3D BIM (Revit -Ifc), WSN enabled IoT, Cloud computing	
(Lu, Xie, Parlikad, Schooling, & Konstantinou , 2020)	BIM, IoT(RFID,QR Codes, Sensor nodes) Cloud Computing	
(Lu, et al., 2020)	BIM (Autodesk Revit -Ifc), City Information Model, GIS, UAV Point Cloud Scanning, Laser scanning, Photogrammetry, BMS, SMS, AMS, WSN enabled IoT, QR Code, Cloud Computing (Dynamo NoSQL (AWS), Autodesk Forge API, Web based Program(.NET) in C# OR JavaScript, ETL ,ML algorithms	
Benefits derived from Implementation		
(Küsel, 2020)	Conceptual Framework for MBSE DT development for Real Estates and Large Portfolio building owners	***Benefits /Value addition***
(Lu, et al., 2020)	Continuous Asset condition monitoring, efficient and automated asset monitoring in daily O & M practices. Predicting useful life of assets	

(Peng, et al., 2020)	10% satisfaction in management satisfaction, overall 1% save in energy consumption annually, 10% of facility faults and requested repairs avoided	
(White, et al., 2021)	Enable citizens give feedback on proposed developments, Enabled citizen reports faults, and city/urban planners plan for emergencies	
(Lin & Cheung, 2020)	Enable monitoring of environmental quality and safety as well as decrease energy consumption and operating cost	
(La Russa & Santagati, 2020)	Ensure continuity in preventive conservation of historical buildings in a non-invasive way through passive strategies and optimisation of existing systems in the absence of professional or monitoring systems	
(Lu, et al., 2019)	Developed a DT at Building level capable of monitoring of as-is condition of building and Predicting remaining useful life of Assets	
(Xie, et al., 2020)	Enabled automated identification of indoor environment anomalies without excessive intervention from FM Enabled site worker to locate and repair corresponding failed assets, faster and related information	
(Heaton & K.Parlikad., 2020)	Proposed a conceptual framework for developing a DT from Asset Information Model	
(Khajavi, Motlagh, Jaribion, Werner, & Holmstrom, 2019)	Proposed framework to enable arrangement of WSN IoT sensors on a building façade to enable ac systems source air from the cooler part of the building outdoors rather than expend energy to cool and recirculate the same air. (Monitoring)	
(Lu, Xie, Parlikad, Schooling, & Konstantinou, 2020)	Developed framework for smart DT enabled asset management into O&M	
(Lu, et al., 2020)	Provided a system architecture for developing DT at building and city levels	

Table 2 Thematic analysis of literature

4.1.2 Smart Buildings

This theme emerges because of the literature analysis as result of analysis of the need to implement Digital twins in the daily operation and maintenance activities. This theme arises from a couple of the articles as a need to have a smart building the enables users experiences all times comfort and satisfaction as well as enabling Facility Managers take effective decisions easily and faster.

(Lu, et al., 2020) described the difficulties involved in daily operation of these systems during the detection of anomalies as the time it takes to query, checking, verifying, and analysing information from these heterogenous various systems including overlapping of data, duplication of data and difficulty in detecting anomalies because of over reliance on the knowledge and decision based on facilities managers.

In the case of a hospital, (Peng, et al., 2020), described how operations requires that they be divided in public, medicine, clinical, surgery and other technical region with high standard requirement for the Operation and Maintenance phase. There are about twenty (20) different systems used for dynamic data sources, the need for a more intelligent and integrated platform that can enhance the operations of the hospital.

(Küsel, 2020) described how in practice large building portfolio owners are left with non-digital, data format and finding a verified building plan and performance information is difficult due to the various system which either 2D CAD, paper based or outdated and recommended the need for a quick real time insight into as built assets.

Digital twin concept was implemented in each of the cases above to create and integrated platform where query, checking, verifying, and analysing information from these heterogenous various systems are made easy and aimed at improving operation and maintenance phase of the building.

4.1.3 Smart Cities

This theme also arises out of analysing the need for governments, city planner and large-scale building portfolio owners need to harvest data from the various heterogeneous data source available to them to improve the daily lives of citizens.

(Lu, et al., 2020) defined a DT at city level to include a dynamic digital replica of a city that integrated each sub-DT (building, bridges, transportation etc).

A smart city systematically applies digital technologies to reduce resource input, improve its people's quality of life and increase the competitiveness of the regional economy in a sustainable manner. It entails the use of intelligent solutions for infrastructure, energy, housing, mobility, services, and security based on integrated sensor technology, connectivity, data analytics, and independently functional value-added processes. (Gassmann, et al., 2019).

(White, et al., 2021) realising the role citizens play in urban and city development, proposed a DT enabled smart city that will engage citizens and get a lot of valuable feedback on key urban planning and policy decisions over the internet.

(Austin, et al., 2020) also realising high levels of situational awareness as a prerequisite to improving day to day operations and accurate estimation of a future demands on limited resources as essential to healthy and sustainable urban behaviour proposed smart city digital twin that mirrors the physical urban systems through real-time monitoring and synchronization of urban activities. The authors hope it would provide city stakeholders (residents, businesses, planners, and engineers) with enhanced levels of situational awareness and decision-making support for managements of urban infrastructure and services embedded in the space time domain.

Another issue when smart cities are the need to monitor environmental conditions to enhance or maintain air quality and people's health and safety. (Lin & Cheung, 2020) developed a smart city DT based framework for monitoring and controlling the environmental conditions in a garage to maintain air quality and people's health and safety.

4.1.4 Stakeholders Involved and End Users

As indicated earlier the DT concept can be implemented throughout the life cycle of a built asset. The means the process of development requires the input of various players involved in the design, construction and operation and maintenance phase of the building's lifecycle. The AEC industry suffers from fragmentation as a result of the various or different stakeholders involved and the nature of information/data required by each stakeholder. BIM processes and tools have ensured interoperability and integration of all these stakeholders. Similarly, it is essential to look at the various stakeholders involved in the development and adoption of DT. The analysis of the selected literature has a clear picture of which stakeholders are involved and what level of information from these stake holders will ensure interoperability and integration of the DT. This is briefly summarised in the table below

General Contractor's DT consulting team: This stakeholder was introduced (Peng, et al., 2020) during the development of a DT for a hospital's operations through the continuous life cycle integration method. The major role they played was to get involved in the early planning and design phase by submitting requests about data interfaces to owners and designers. Their role also included collecting of important design meta data such as serial codes of assets and location of sensors. This is to ensure consistency between the digital model and the real-world conditions at any time. (Lu, et al., 2020) also introduced Consultants in the process of developing a DT at city levels, and their main responsibilities was to provide project management and collaborative expert support.

Software Developers: The operation and maintenance phase of a building is couple with a variety of software tools used to provide required services and manage daily activities. Commonly adopted software's include CAFM, BAS, CMMS etc All these a developed with the client/users wishes/requirements in mind to enable efficient operation and maintenance activities. However, the proliferations of these systems have made it difficult for FM in accessing the required information at the right time (Lu, et al., 2020). In the analysed literature software developers play the role of identifying system requirements and external interfaces (other systems, suppliers, and data) needed in developing the DT (Küsel, 2020).

End Users (Building Operators, Facility Manager, Urban City Planners, Government):

As stated in earlier chapter, DT can exist for a variety of purposes, spatial spaces, temporal scales and approaches to modelling, and as such before the process begins it requires the clarification of the end user's needs.

(Küsel, 2020) was guided by a specific KPI's relating to its client's maintenance and management contract, including the completion rate for planned, preventive and reactive maintenance tickets, reduction in energy consumption across the duration of the contract and an increase in rental yield across leased space.

In the case of (La Russa & Santagati, 2020)it was for the need to address managements of thermo-hygrometric conditions for preventive conservation of museum collections in buildings with high historic values in the absence of qualified professionals and/or a monitoring system.

These end user requirements are essential during the development of a DT as it will detect the various sources of data in which to rely on during the development process.

4.1.5 Enabling Technologies

This chapters analyses the enabling technologies that was used in the development of the digital twins from the shortlisted research articles used for the analysis and discuss the benefits and reasons behind the use of these technologies. This was also done to establish what constitutes the Digital Twin Concept.

BIM and Internet of Things

BIM as a digital representation of building and civil infrastructure can be extended to form the basis for a database of all assets facilitating exchange of information in a unified and digital manner and it can also be used as an information source and repository at the same time supporting various activities in existing building and infrastructure (Lu, et al., 2019) (Xie, et al., 2020). This is however not the case in most instances as, clients, building operators are handed over 2D CAD drawings and specifications and only in some instances is it accompanied by a Construction Operations Building Information Exchange (COBie) spreadsheet, containing the assets' as-built information. (Küsel, 2020).

(Lu, et al., 2020) undertook a review of efforts being made in integrating BIM into asset management in the Operations and Management phase and highlighted several advantages including, accurate and efficient support for decision making, monitoring and communication, easy retrieval and storage of maintenance, inventory, and operational data and many more. However, the authors stated that despite these advantages the key problems to the implementation and research are unsolved. This they related to the lack of awareness of the potential benefits of BIM in O&M, lack of real-world implementation and the lack of a well organised framework just to mention a few. The briefly summarised the limitation as, technology related issues, information related issues, organisational related issues, and standard related issues. **So the question is how can BIM be successfully implemented in DT in the O&M ?**

(Lu, et al., 2020) relied on the flexibility and consistency of the IFC schema in the building lifecycle. Its ability to be linked with other data sources like sensor data in a distributed manner when the other data source a kept in the original storage. They proposed and extension to the current IFC schema-based O&M activities, required information and process as the core step to the DT construction. Specifically, entities like *IfcProcess* and *IfcConrol* were extended to add subclasses entities *IfcOperationandMaintenanceProcess* and *IfcOperationandmaintenanceControl*. Also, *IfcAsset* to be extended to match the specific O&M needs. Extra extensions included *IfcMaintenanceHistory*, *IfcInspectionHistory* and *IfcSpareRecord*. Integration was done through linking of the BIM objects GUID and the corresponding database IG for other data source (AMS OR BMS).

(Heaton & Parlikad, 2020) also attempted an approach for developing an Asset Information Model and BIM to support the creation of a DT. The authors proposed the use of a classification system (UNIClass) in a BIM environment based on functional output, development and AIM relational database derived from the exported ifc models and lastly the BIM models being linked with the database base within a federated model.

Another issue that came up during the analysis is that, about 80% of buildings in EU were built prior to 1990 and as such do not have a BIM model to start with (Khajavi, et al., 2019). However technologies like stereoscopic areal photography, lasers scanners, photogrametry, terrestrial laser scanning(TLS) and structure from form(SFF) techniques have enabled capturing of 3D models of old building through the Point Cloud to BIM approach (White, et al., 2021) (La Russa & Santagati, 2020) (Peng, et al., 2020).

According to (Xie, et al., 2020), modern building management systems (BMS/BAS) are pre-programmed to trigger and alarm when anomalies occur from the energy perspective and from an indoor environmental perspective (room temperature). The systems make use of sensors that are proprietary sensors and the data they collect are not accessible or available for analysis. This challenge is however overcome with the introduction of IoT enabled wireless sensors networks for data acquisition. WSN refers to a collection of distributed and dedicated sensors for monitoring and recording conditions of environment and equipment (indoor temperature, relative air humidity and equipment conditions such as component vibrations, surface temperatures and the speed of rotating parts (Lu, et al., 2019). What makes WSN enabled IoT sensors most suitable for DT purposes includes.

Its ability to support data uploads from sensors deployed at distributed locations and its scalability to support large number of assets (Lu, et al., 2019).

It also has the advantage of small dimensions, low price, and power consumption, including its ability in environmental detection and active network, they are widely used in smart cities, environmental monitoring etc.. (Lin & Cheung, 2020)

(Khajavi, et al., 2019) further explained WSN enabled IoT as having emerged as a ubiquitous global computing network where data from affordable and available sensors and actuators can be used for analysis-based control of resources or assets.

WSN enabled IoT sensors are made of sensors nodes and getaways nodes. The sensor nodes measure environmental conditions such as indoor temperature, relative humidity, speed of rotating parts and surface temperatures whiles the gateway nodes are used as the bridge between local sensors and the remote applications like cloud databases or online webpages to visualise the data (Khajavi, et al., 2019), (Lu, et al., 2019). From the analysis the sensors are connected to the gateways either through Bluetooth low energy communications (Khajavi, et al., 2019) or through radio frequency (RF) (Lu, et al., 2019).

Finally, the sensing and controlling capabilities of WSN enabled IoT sensors in collecting the data about the environment including carbon monoxide (CO), temperature and humidity and the ability of BIM to communicate by 3D illustrations are the main reasons why they are ideal for DT applications. With respect to integration and interoperability, WSN enabled IoT sensors provides active information from real world and enables a BIM model to be act as the DT showing real time status in accordance with dimensions and positions of observation (Lin & Cheung, 2020).

(Lin & Cheung, 2020), (Khajavi, et al., 2019) and (Lu, et al., 2019) present a systematic way of setting up the WSN enabled IoT and connecting it to external applications like the cloud or web applications. The hardware framework of the WSN sensor nodes are constructed Microsoft. NET Gadgeteer embedded systems and the functions are designed by the .NET Micro Framework of Microsoft (.Net MF).

Cloud Computing and Big data Methods

Authors like (Peng, et al., 2020) applied a lightweight algorithm to reduce the size of primary geometry data accumulated during the design and construction stage, however when it got to dynamic data during the Operational phase from various heterogenous source the author recommended big data services powered by free open-source engines (kafka and flink). According to (Peng, et al., 2020) the process of continuous integration led to huge accumulation of data leading into terabytes of both static and dynamic data required big data analytics developed at backend to consistently display high density data streams. This is due to their ability to process and transform quick and stream data from various sensors. (Lu, et al., 2019). (Lu, et al., 2020) also proposed that for IoT to support heterogenous environments its architecture should include big data techniques and cloud computing to improve its performance.

Intelligent Algorithms and Machine Learning Algorithms

(Peng, et al., 2020) applied machine learning algorithms like *k means clustering* in detection of abnormal electric usage, *Long Term and Short-Term Memory (LSTM*) for predicting faults in Air Handling Units and *open-source algorithms* for detecting frequent repair patterns. (Lu, et al., 2020) also applied machine learning algorithms like *Long Term and Short-Term Memory (LSTM*) to estimate the characteristics of Building energy demand.

In the absence or real live data set from a building (La Russa & Santagati, 2020) used synthetic data sets as compensation and applied machine learning algorithms linked to multivariate linear regression in design a Decision Support System (DSS) with two parameters (external climatic conditions and internal prevention actions)

(Xie, et al., 2020) used unsupervised machine leaning algorithms (statistical methods) including Moving Average (MA), cumulative sum (CUSUM) and binary segmentation-based change point detection methods to detect anomalies in environmental data.

4.1.6 Benefits and Value Added

Whiles the DT concept is relatively new concept in the AEC industry, a review of some of literature and use cases clearly shows the benefit and value addition the concepts bring to the current state of building operation process and activities. (Peng, et al., 2020), after developing a DT and using it for a year resulted in 10% satisfaction in management satisfaction, overall, 1% save in energy consumption annually, 10% of facility faults and requested repairs being avoided. Highlights of the major benefits derived from the implementation of DT is detailed in Table 2 above.

5 Interviews

As part of answering the research questions, professional knowledge and experience was sought in the form of three semi-formal interview. In the case of this thesis, the interviewees were picked based on the identified stakeholders from the systematic literature analysis namely Facility Managers, Building Managers as well as people who are working with Facility Management Systems and Building Management Systems in the AEC industry as well as software developers and Consultants in the AEC industries. Table 3

Name	Profession	Role in O&M
Interviewee A	Head, Maintenance Department (University Estate Management Department)	Building Management Systems User (Schneider Electric)
Interviewee A	Technician (University Estate Management Department)	Building Management Systems User (Schneider Electric)
Interviewee B	Software Developer	Facility Managements Software Provider
Interviewee C	Consultant/Product Owner	Facility Managements Software Provider

Table 3

The first interview included two people being interviewed at once. These people were the Team Leader of the Campus Service and a Technician at a University's Estates Department. They introduced the Building Management System of the university to demonstrate how the system operates. The other interviews were conducted with the goal of supporting the general problem statement of the paper. These interviews were conducted with a Product Developer at a Facility Management software company, "Consultant/Product Owner" at company that provides facility management services, to gather information about their insights and perspective about Digital Twin concept in the AEC.

5.1 Interview A

The first interview introduced the Building Management System (BMS) used by Aalborg University of monitor the various systems in their portfolio. The BMS system used is provided by Schneider Electronic, and the interviewee expressed his satisfaction with the system and its ability to be remotely accessed and monitored in these COVID 19 time.

'We're very pleased to have this system especially in this Corona times where we all sent home because we can actually monitor most of our systems from our from home…'

The system basically controls and monitors all the technical systems in all the buildings on AAU campus including Ventilation systems, Hot water systems, cooling systems alarm systems etc. It monitors and controls these systems by the Set Points method with the help of sensors that provide real time data on indoor environmental conditions and efficiency of critical components etc. Alarms are triggered when there is a fault in operation and these alarms are prioritized in order of criticality. Alarms automatically send SMS to technician and enable them respond in time. The system also displays real time visualization of indoor environmental conditions and critical values or relevant data for these systems. The supports temperature setpoint enforcement, separate heating and cooling setpoints, programmable occupancy schedules, auto demand response (zonal level).

'*So when we click on so that we can actually see all the measures and at most of the other components that are relevant to have data on a ventilation systems …We can see where the air comes in and out, and we can see all the values, so we can see what are the temperatures before the heat exchanger, we can see the values, see how fast are the ventilation running, is the heat on is it off, is the cooling on…'*

Regarding how intelligent the system is, for instance in responding to outdoor weather condition, the interviewee mentioned that depending on how modern the building is and how much money was invested in the building, some of the have the ability the change the operations in response to outdoor environmental conditions.

'Depending on how modern and how new and how much money there was on building the buildings at the system are more or less advanced and more or less intelligent. In a normal study group, you will have a so called IPI zone where controller controls the heating valve for the radiator and the valves for the ventilation ducts, and if it's if the CO2 level rises it provides more air to the room, if it gets too cold the valve for the radiator opens.'

Enquiring on whether the system applied any Machine learning algorithms or intelligent algorithms to help predict the failure of assets or performance of these systems the interviewee highlighted the peculiar nature of building operations which rely on experience and knowledge of Facility Manager/Technicians and the cost involved as the reasons why they did not continue with its implementation. He however acknowledges that future potential in such algorithms.

'*what we discovered is that this is too new it's not efficient enough we use a lot of money on buying the module but it is too, 'to cry out loud' an 'idiot' can tell us what intelligent algorithms for explaining to us and therefore we said thank you but no thank you we did a proof of concept but it was not efficient enough but I definitely think that that would be the future but within a couple of years it would probably be more intelligent and efficient than it was two years ago''*

Another thing the interviewee highlighted was his interest in the IoT technology. He mentioned the wireless nature, cost as well as the fact they give more information about things,

'*Something that we also are interesting in is the IoT technology or basically making things not wired to chill about the wireless. We are often construction new rooms and buildings and it's very expensive to have cables and communication between each component and it is a bit old* *school if you ask me. I wanna do it at wireless I wanna have more IoT that can measure more things so that we can they reduce energy even more and have more better indoor climate so that is the IoT technology is really an interesting thing to put into BMS systems….'*

5.2 Interview B

The second interview was done with a systems developer whose company has a Facility Management system. The systems support operation and maintenance processes and activities. The system is made up of several modules including work orders and BIM, asset management module etc.

'..we have a 3D viewer and we have a lot of functionality with it's based on modules .So we have a module for or even say tasks(work orders) and we have one for helpdesk that's the users of the building how do they say something is wrong with my building we have something for assets that would be your components in some way we can also be linked to objects and so you can think it altogether documents in general have a module for that. But how we say we connect all of these modules so all that information can flow across and can all be connected but depending on what your resources are that's also where you place yourself in the digital part….'

The system however relies on integration with other systems to keep updated and the interviewee highlighted the luck of a standardised way of doing these integrations as a major limitation to their system.

'..I don't know you can say if you look at the very broad spectrum and every system uses their own way of integrating to other systems meaning that when we when I have some data in Dalux then we expose the data through an API and if somebody wants to extract it then they can connect to our API and extract it and then put it into their own system the same way if some people want to push data from another system into our system our API extracted through the API and then they push it into our system through our API but we use some one way of doing it and they have another way of doing it but there's no general you can say that no you still need to be a developer to do this.'

On the use of intelligent algorithm or machine learning algorithms in their systems to predict future performance of assets etc, the interview indicated that he is yet to see a use case that requires the use of these technologies.

'*…but there could be a lot of potential on that part but it's I haven't seen the good use cases the building industry yet but I think they could be really hard for me to say. I think there is a lot of potential in the future..'*

5.3 Interview C

The third interview was conducted with a product developer /consultant at facility management software company, and he introduced their systems. This system supports functions like helpdesk on buildings, task and resource management, calendar systems and day-to-day tasks of service employers on site and with integrations to drawings at 3D or 2D drawings.

‘‘This system is a broad system which can support functions like helpdesk on buildings, task and resource management, calendar systems and day-to-day tasks of service employers on site and with integrations to drawings at 3D or 2D drawings. Also, it’s expected that you gather data regarding your buildings in one system so if you could you go to, for example the municipality of Copenhagen, they have all their buildings in our system, and this is the main system where they have all the buildings and then integrations from there to other systems. So we collect all the data surrounding the buildings or connected to the buildings in NTI-FM with integrations to ERP systems and some organizational systems etc.”

He further explained that for their system to be integrated with real-time data or IoT data, an IoT hub needed to be set up in front of their system. He however said that, integration with IoT database was part of their plans for 2021;

‘We are working with a few companies that are developing in this area and if we're doing like IoT sensors and real time data, you must have an IoT hub in front of our system so, for example what we are working with it is called an Azure IoT Hub to gather all this real time data, and you have the assets in our system and you connect that to the IoT hub and then from the IoT hub you are able to identify patterns when some specific intervals are over written and then you can create an alarm or a task into the FM system to the service provider to go check the pump for example..’

On whether the system applies intelligent algorithms or machine learning algorithms to predict future performance or maintenance of assets. He explained that they had a prediction module that makes 10–30-year plans of maintenance cost and these are based on both visual inspection of assets and experience rather than intelligent algorithms.

‘We developed something called 10 or 30 year plans, where you can predict what the maintenance costs of the building is 30 years ahead, and that is done by visual, so people like us, go and watch the buildings and put it in the end in the system, and we are right now developing that we can connect it to what we know as predictive maintenance, which is not implemented in very many places yet, where predictive maintenance is using sensors to automatically maintains this maintenance plans and I don't think that anyone in Denmark is at this moment, but I think some of the big building owners is going there and some of the private building owners might be there now but the public building owners are not there yet. This is my understanding, but I'm not sure. But this is coming, this is the future.”

He however expressed that with the increasing nature of data in operation and maintenance it likely to be necessary in the near future.

“I mean I had a customer two weeks ago that said to me “oh do you do you have machine learning in your systems? We want to put up some assets and then put in a few values and written when that value is exceeded, you need to create a task for the maintenance plan. And that is in my opinion is not machine learning. But that's not machine learning and AI, AI and machine learning is that some cloud computing is able to identify patterns in your data and it suggest things that need to happen and I think there's a I think the industry to my knowledge not there yet, but I mean the digitalization is going very very fast this moment so it's a matter of time before the it’s there. So we are working in that direction to digitize buildings and to be ready for it. We actually have developers employed who has knowledge to machine learning.”

Highlights of the interviews are summarised in the table below.

Themes	Interviewee A	Interviewee B	Interviewee C
Remote Monitoring	Enables user to remotely monitor and controls building technical installations	Enables user to remotely access information through mobile devices	Enable user to remotely monitor assets and access information relating to building and assets
Visualisation	Realtime visualisation of indoor environmental conditions and critical components performance (2D)	Enables 2D/3D BIM visualisation of building and its systems	Enables 2D/3D BIM visualisation of building and its systems
Integrations with other systems	Enables integration with other systems e.g., booking systems	Lack of standardised way of integrating with other systems is major problem	Enables integration with other systems through web-based programs
IoT integration	Part of plans for 2021-2022	Not seen any good use case in FM to requires it	Part of plans for 2021-2022 looking at integration with BIM 360 and Autodesk Forge
Predicting Future Performance with Intelligent Algorithms or ML Algorithms	Due to peculiar nature of system, it proved in efficient, however it is expected to be the future	Cost involved in developing and maintaining such a system normally outweighs the value derived	Currently based on human visual inspection and experience, hoping to use IoT Integration and analysis to develop and predictive maintenance module

5.4 Summary

In summary the BMS systems are operated based on set point systems, which means that sensor provides measure of components in the building and when these measures/value reach below or above a set measure/value the systems trigger a response in terms of turning on/off or triggering alarms and also sending notifications to technicians. It was also realised that this form of automatic control system which is known as Direct Digital Control often exist in new building which a lot of money had been invested in an example being the Thomas Manns Vej building (TMV23). Most buildings in Europe were built prior to 1992 and hence have pneumatic control systems and as such efforts needs to be made to modify these controls into DDC to enable the implementation of the Digital Twin Concept. These older pneumatic control systems do not support set point systems, programmable occupancy schedules, auto demand response like the one encountered in the interviews.

The facility managements systems were also faced with the limitations of the lack of digital copies/models of building portfolio partly due to the same reason and a lot of efforts must be put in acquiring digital copies of building in situations where no building plans or documents existed.

6 Findings and Discussion

The chapter deals with answering the problem formulation and it is structured in three main broad topics that captures the research questions in general. These are discussed in detail based the analysis of the data from both systemic literature review and the interviews.

6.1 Current Status of Digitalization in the Operation and Maintenance Phase

Analysis of both interviews and systematic literature review presents the author an overview of what the status of digitalization in the operation and maintenance phase of the building life cycle. This has been discussed in themes to highlight the status of digitalization in respect to the achieving the implementation of the digital twin concept. These themes relate to Building Management Systems (BMS) and facility management systems (FMS) that was included this report.

In general, current Facility Management systems (CMMS) and BMS have the potential to monitor and controls assets remotely. While Facility Management systems (CMMS, Asset Maintenance), enable 3D visualization of building models and technical installations, a lot more effort has to be put in acquiring digital models of these buildings. This was highlighted in the interviews as follows.

Interviewee B highlighted as part of his duties involved digitalizing the building portfolio of a client who own more than 5000 apartments in Denmark. This was necessary for him to get a good overview of all his properties and effectively monitor usage and maintenance activities.

'We had 2.5 million square meters of buildings and we needed that digitized and we, so we started creating models of all our buildings and measuring them in general because we didn't have any material than old drawings and stuff like that'.

This process involve scanning of existing buildings **using stereoscopic or arial photography or 3D Point clouds** to get digital models of these building and systems (Heaton & Parlikad, 2020), (La Russa & Santagati, 2020), (Peng, et al., 2020). The maturity level proposed by (Evans, et al., 2019) proposes reality capture as an essential element in capturing as built data set of an asset.

Interview C also highlighted the fact that in practice most of the large-scale property owners do not have a digital model of their building portfolio and they are often in paper formats and a such a first major step is to use the stereoscopic **or arial photography or 3D Point clouds** for acquiring these digital models and subsequently been able to automate tasks etc.

'And I think one of the things that the problem is digitalization, some of these building owners don't have all the data registered, it is on paper. so, I think that is one of the biggest problems is that our customers, most of them don't have this data registered in the system and some does."

6.1.1 Remote Monitoring and Control/Visualization (3D BIM)

While both FM systems or developers interviewed, involved visualisation of building, and building systems in 3D geometry with integration with BIM models and Asset Information Models as a major component of the systems, the BMS system in interview A still relied on 2D CAD visualisation for monitoring sensor values of critical components and visualising indoor environmental conditions (temperature). Interviewee A(Technician) expressed his satisfaction with the 2D CAD; however, his supervisor recognised the impact 3D visualisation can have in future.

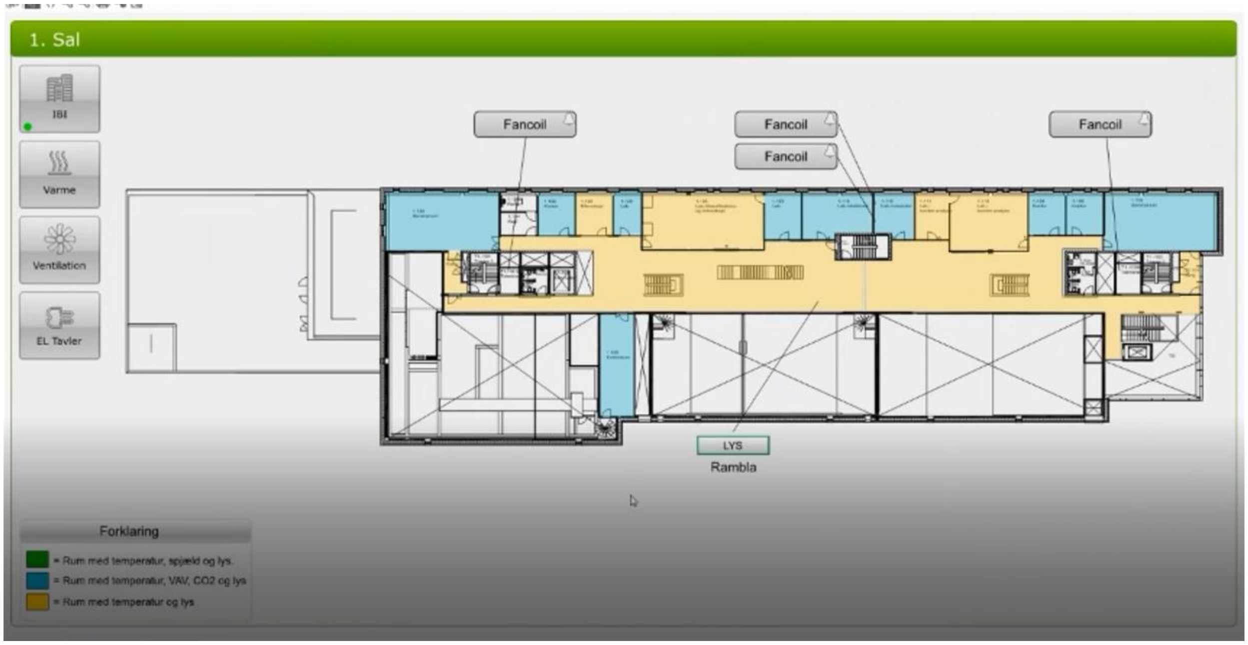

Figure 17 Display of real time indoor temperature conditions of rooms in 2D Source Interview A presentation

However, (Lin & Cheung, 2020) demonstration of how a DT concept can be applied to monitor environmental conditions shows what visualisation of these same conditions will look like in 3D view. This is illustrated in figure 18

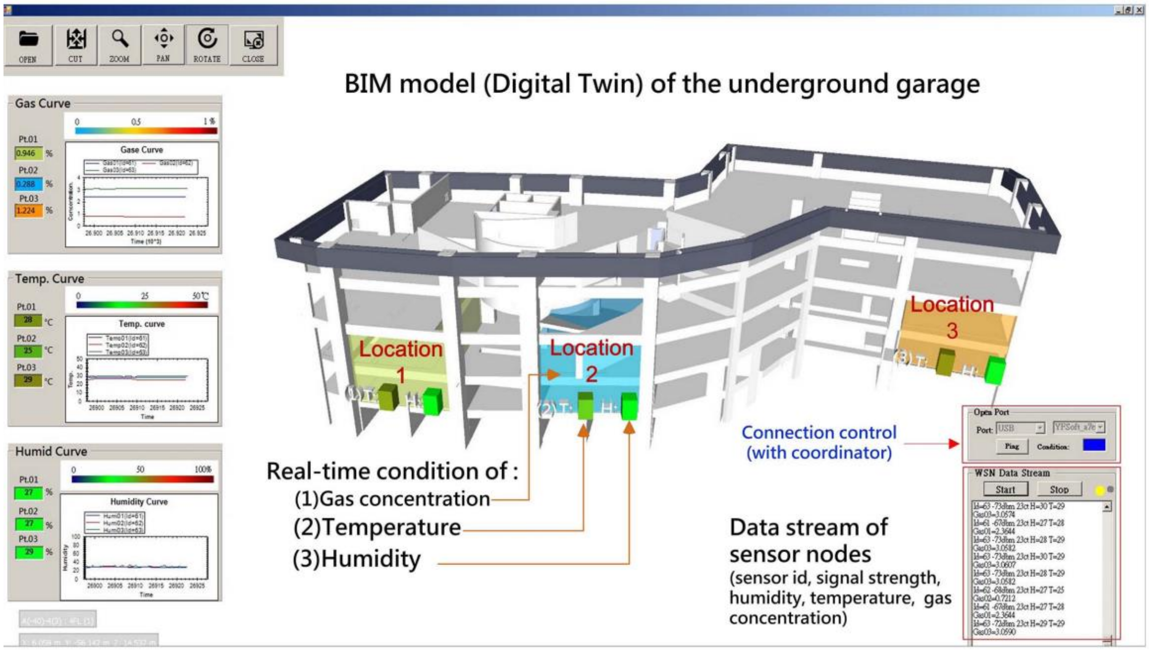

Figure 18 3D visualization of indoor environmental condition using the WSN enabled IoT integrated DT Source: (Lin & Cheung, 2020)

Interviewee C also explained further that having these 3D Models are very important during their energy optimisation process because it enables them figure out per square what building contribution to CO emission is etc…

'*And you have the ability to calculate let's say CO2 consumption of buildings as well, so you can look at the buildings and how much CO2 is these buildings consuming and because we have the drawings you can do that per square meter, so we use the drawings as well and that's something that is unique to our systems regarding some of the Hubs that combined this consumption data with square meters from these drawings."*

While modern building management systems are capable of remotely controlling based on ***temperature set point, separate heating and cooling setpoints, programmable occupancy schedule and auto demand responses on zonal level*** which leads to effective energy saving etc. However there exist a significant amount of buildings whose operations are still based on pneumatic controls which are characterised by mechanised devices (no communication, no data, no remote control), wastes energy, higher maintenance cost, no fault detection or notification and uncomfortable occupants. Therefore, efforts must be put in converting these pneumatic controls to Direct Digital Controls which will further implementation of the DT concept.

6.1.2 Internet of Things and Integration

Current operation and maintenance systems allow integration with other systems to enhance operation and maintenance activities. The BMS are often integrated with Booking systems, this allows the BMS systems to for example heat up or cool down meeting rooms some hours before the rooms are used. This ensure optimal indoor environmental conditions and consumption of energy is reduced. The Facility management systems are also integrated with other systems for example booking systems and maintenance systems (CMMS) to enable effective practices. However, these integrations are done differently depending on who the developer is or the specific API. This presents a major limitation. This is highlighted by interviewee B as the lack of standardised way of doing these integrations.

‘So there is no standardization of the way to extract data across these integrations between the components that you might have inside of the buildings and the booking system for example that's not building system so they would never look at this so we cannot cover it all but it could be some regarding the extraction of data and pushing data from one system to another... so if there was a standardized way of doing this would be easier to build these’

While interview A and C also identified IoT technology as a major thing missing for major operation and maintenance systems. Interview A stated that his main interest with IoT has to do with the fact the its wireless, cheap and provides even more data about daily operations than the current sensors being used.

‘Something that we also are interesting in is the IoT technology or basically making things not wired to chill about the wireless. We are often construction new rooms and buildings and it's very expensive to have cables and communication between each component and it is a bit old school if you ask me. I wanna do it at wireless I wanna have more IoT that can measure more things so that we can they reduce energy even more and have more better indoor climate so that is the IoT technology is really an interesting thing to put into BMS systems.’

Interview C also acknowledge the potential of IoT and stated how integration their FM system with an IoT hub can help identify patterns and helps create task into their system. He however said that it is expected to be explored later in the year 2021.

“an Azure IoT Hub to gather all this real time data, and you have the assets in our system, and you connect that to the IoT hub and then from the IoT hub you are able to identify patterns when some specific intervals are over written and then you can create an alarm or a task into the FM system to the service provider to go check the pump for example. In regard to the question, I can sense that you ask if we have that in our system, and we don't and I don't think in general that the FM systems have that Hub, I think they use integration to other cloud computing at IBM or Microsoft IoT hub or any other”

In the systematic literature (Lu, et al., 2020) described how IoT sensor data can be integrated with asset/sensor data provided by the BMS systems by hardwiring the data collected by BMS controller, using a TREND SIP interface to allow capture of BMS data at intervals and later uploaded as CVS files to a simple mail transfer protocol (SMTO) server. Later a BMS Data integrator software was used to read the data stored in CSV files in SMTO server and upload it to a cloud database for web applications. This is integration was done using Autodesk Forge API, web-based program (ie .Net) using C# and java script.

This is what Interview C also highlight as part of the focus this year 2021 looking at integration IoT data using Autodesk Forge API,

‘So that is in the roadmap this year, so integrations and some functions need to be better at this moment, and then for the start of next year at this moment, but this this can change, it is IoT and

it is integrations to what called BIM360, Autodesk Forge .. if you know that product from Autodesk.'

6.1.3 Use of Intelligent Algorithms/Machine learning algorithms for Predicting Future Performance

From the literature review, it was clear that one of the main characteristics about DT was its ability to use the data heterogenous amount of data acquired to predict future performance or failure of assets/systems. Intelligent algorithms like cumulative sum (CUSUM), *Long Term and Short-Term Memory (LSTM*), was applied in detection anomalies and predicting faults in various critical assets during operations (Xie, et al., 2020), (Peng, et al., 2020).

While interview A explained that they had tried an additional module that predicted performance to aid the facility manager is their daily routine, he believed the peculiar nature of the system makes such a model inefficient..., So most BMS systems currently do not possess the ability to predict performance of failure of assets.

'... we discovered is that this is to new it's not efficient enough we use a lot of money on buying the module but it is too I sing it out loud and 'idiot' can tell us what intelligent algorithms for explaining to us and therefore we said thank you but no thank you we did a proof of concept but it was not efficient enough but I definitely think that that would be the future but within a couple of years it would probably be more intelligent and efficient than it was two years ago'

Whiles Interview C indicated that they currently have a module dedicated to predictions a 10-30 years maintenance plan/cost, it was clear that these predictions were based on visual inspections of assets and specialists knowledge.

"That is one of the premises our system. We developed something called 10 or 30 year plans, where you can predict what the maintenance costs of the building is 30 years ahead, and that is done by visual, so people like us, go and watch the buildings and put it in the end in the system'

6.2 Proposed Components of the Digital twin Concept/System for Operation and Maintenance

Based on the knowledge obtained from the systematic review, the interviews and the current state of digitalisation of O&M discussed above, this author proposes a conceptual framework that aims to capture the components of the Digital Twin Concept. As seen, the Digital Twin is not a technology by itself but rather a concept the embraces the integration of other technologies like BIM, AR, Cloud Computing, Machine learning algorithms etc. and the main capability of this concept includes

- Enabling realistic (3D) visualisation of the real time operation of a building asset and its technical installations.

- Enable remote control and monitoring of building performance and assets

- Predicting of future performance of building assets and components including predictive maintenance
- Ensure users obtain the expected satisfaction during daily operations
- Ultimately achieving an automated operation and maintenance

The proposed conceptual frameworks shown in figure 19 and briefly shows the components of the digital twin concepts in four (4) layers .

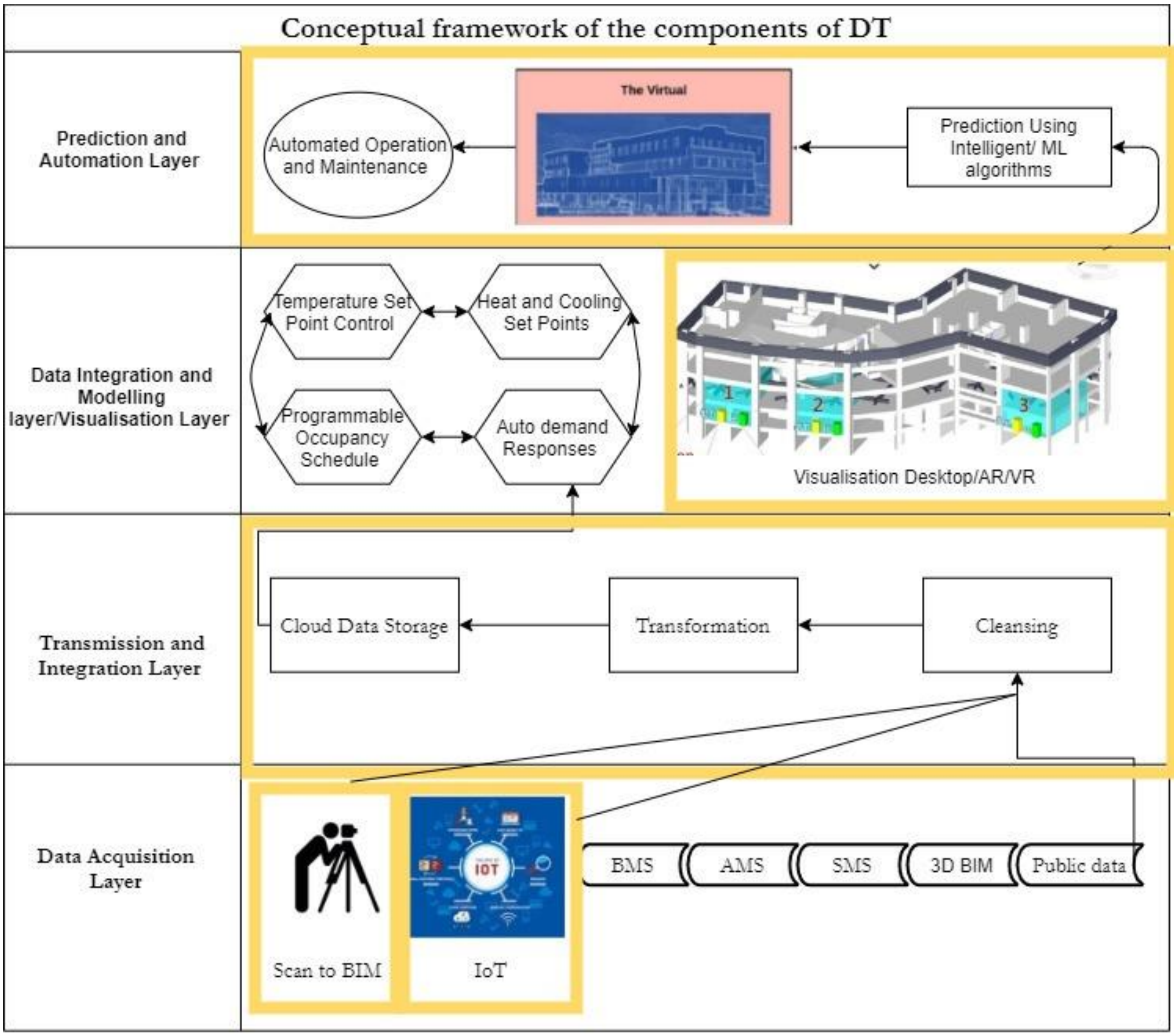

Figure 19 Proposed Conceptual Framework showing the components of DT

The highlighted components show the limitations (authors perspective) in achieving the full implementation of digital twin concept. These are the areas or technologies that require efforts to enable the full implementation of the DT concept.

Data Acquisition Layer

This is the first and most important step in the digital twin concept and it not only involves capturing the digital properties of the physical assets involved. But it also involves identifying the relevant data sources that will be needed in developing the DT. As indicated by the Gemini principles every digital twin must be developed with a specific purpose in mind. This purpose informs the required sources of data. **Scan to BIM** technologies including 3D point clouds from laser scanners, photogrammetry, terrestrial laser scanning(TLS) stereoscopic or arial photography (White, et al., 2021), (La Russa & Santagati, 2020)and (Peng, et al., 2020). These are necessary when the 3D models of building do not exist and in Europe where 80% of buildings were constructed prior to 1990 (Khajavi, et al., 2019). Current building operations is also characterised by heterogeneous systems that capture and store data for different purposes including CMMS, BAS, ERP, AMS etc. therefore the purpose in developing a DT will determine which of these systems data is required. In the case of (Peng, et al., 2020), a **Digital Twin Consulting group** on the contractor's team were responsible for identifying the needed data sources during the design and construction phase through a process the authors referred to as continuous lifecycle integration. This role is also supported by (Loscos, et al., 2019) part of the responsibility of a Digital Twin Manager including identification of public data to be used in the development of the DT. (White, et al., 2021) relied on public available data **(OpenStreetMap)** for data about power, public transport, motorways, highways during the development of a DT Smart city. WSN IoT technologies can also be used in the case of new construction of building or renovations or in the absence of and automated building management systems, due to the benefits the present. Other sources of public data can also include weather and climate data etc…

(Lin & Cheung, 2020), (Lu, et al., 2020), (Lu, et al., 2019) provide a systematic approach including the components of a WSN IoT enabled network can be developed according to the functional requirements and integrated with BIM models.

Transmission and Integration Layers

The massive amount of data gathered at the data acquisition stage during operation and maintenance is usually consists of various source of dynamic and static data including both structured and unstructured data. This requires the services of clean, transform and storage or data pre-processing and data management. (Peng, et al., 2020) described how huge volumes (10 terabytes) of data can be easily generated a day during the operation and maintenance phase of a building and relied on free big data services powered by free open engines to transform, process, and store these data. The main providers of these services include, **Amazon Web Services (AWS), Google Cloud and Microsoft Azure**. During the transmission of the data collected, it is attached to physical assets/spaces of a building, and various communication tools used like 5G, low power wide area networks (LP-WAN) and WLAN. (Lu, et al., 2019). ***Extract Transformation Load (ETL***) technologies are used in the identification of relevant information at the source side, (b) the extraction of this information, (c) the customization and integration of the information coming from multiple sources into a common format, (d) the cleaning of the resulting data set based on database and business rules, and (e) the propagation of the data to the data warehouse.

Data integration and modelling /Visualisation Layer

To visualise the dynamic operational data gathered from the various heterogeneous systems, it is essential to integrate the BIM model with these data sources to give insight and enable informed decision making. (Lu, et al., 2020) , described how the integration layer must be capable of integrating and interoperating external data relating the BIM object in the digital model on a semantic level and relied on ifc schema to represent components, attributes, properties, relationships and linkages with other libraries or data sources using Autodesk Forge (API), AWS and web-based program design (i.e. .NET) using C# and Java Script. Autodesk Forge is uniquely suitable for this integration because it enables leveraging design and engineering data to develop custom software application and custom workflows (Forge, 2020). The (Forge, 2020) platform allows.

- 3D models to be viewed from a browser allowing embedded interaction and retrieval of metadata in over 50 formats.
- The API allows access to data across A360, Fusion and other Object Storage services
- The API can also prepare files for the viewer, extract geometries, retrieve metadata from over 50 different industry formats

Depending on the purpose for developing the digital twin, visualisation can be done in the form of dashboard display of digital model and its associated data either indication indoor environmental conditions (Lu, et al., 2019), through AR/VR visualisation to enable detection of anomalies (Xie, et al., 2020), or visualised resources allocations to optimise maintenance activities. **Figure 20** shows how building as-is building operational data can be visualised in the integration layer.

Interview C also talked about their plans to improve integrations in their systems using Autodesk Forge, BIM360 beginning 2021 -2022. This is also because the company is Autodesk's biggest reseller in Europe.

'So that is in the roadmap this year, so integrations and some functions need to be better at this moment, and then for the start of next year at this moment, but this this can change, it is IoT and it is integrations to what called BIM360, Autodesk Forge if you know that product from Autodesk'.

Example of how visualisation can be done in this layer using Autodesk Forge is shown in fig 20 which shows the indoor environment condition.

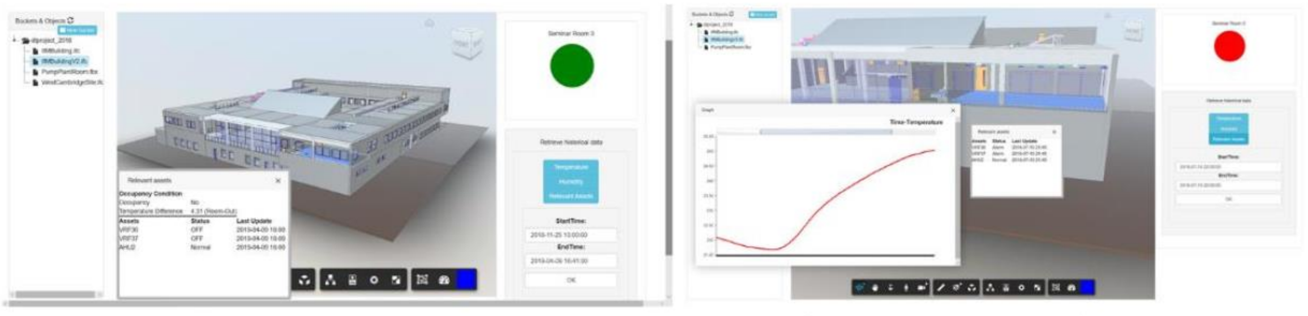

Figure 20 Visualization of indoor environmental Conditions and maintenance plan schedule by (Lu, et al., 2020)

(Lin & Cheung, 2020), also integrated WSN enabled sensor data with BIM models using Revit, Navisworks (API), web-based program design (i.e. .NET) using C# and Access (figure 18). Another example of visualisation in this layer is shown in **fig 21** where (Peng, et al., 2020) developed a real-life DT of a hospital by integrating BIM models and heterogeneous data from other databases to enable effect administration of hospital operations.

Figure 21 Real time visualisation of energy consumption in a hospital through DT implementation (Peng, et al., 2020)

It is in this layer where existing traditional intelligent control logics that includes temperature set point, separate heating and cooling setpoints, programmable occupancy schedule and auto demand responses on zonal level etc which leads to effective energy saving etc are applied. (Peng, et al., 2020) applied intelligent algorithms like K cluster algorithms to continuously monitor electricity consumption and identify any abnormal meter that exceeded 20% threshold of normal behaviour. This automatically sends notifications to technicians to locate related facilities and stop unnecessary energy consumption.

Prediction and Automation Layer

Acquiring and storing these data over a period provides a good basis for analysis these data and applying intelligent algorithms and other prediction models to optimise operation and maintenance tasks. This layer is one of the unique components of the DT concept. Even though **Interview A and B** stated that the cost associated with developing these intelligent algorithms or applying machine learning algorithms usually outweighs the value, Interview C recognised how these will benefit the industry in the long run. The benefits are highlighted through the systematic review.

(Peng, et al., 2020) applied intelligent algorithms like Long Term and Short-Term Memory (LTSTM) network to effectively predict faults in Air handling Units there by notifying technicians before the actual faults happen. (Lu, et al., 2020) applied the Bayesians Online Change Point Detection algorithms for detecting anomalies of building assets and predicting the useful life of building assets.

In the absence of stored data in the data warehouse, (Lin & Cheung, 2020) relied on synthetic data sets from publicly available data sets to be able to ensure continuity in preventive conservation actions in the absence on a monitoring system.

6.3 Value addition in the application End Users

Based on the systematic review and the interview analysis the derived benefits from the implementation of the DT were discussed alongside the values proposed by (Beetz, et al., 2020) to see how the benefits relates to these values.

Value addition

Interview A stated the cost associated with implementing predictive modules (ML algorithm etc) in BMS systems as major limitation. He however also acknowledges that the implementation or integration of IoT sensors/technology in the current BMS system will lead to further reduction of energy and better indoor climate due to the advantages the IoT technology.

' I wanna do it at wireless I wanna have more IoT that can measure more things so that we can they reduce energy even more and have more better indoor climate so that is the IoT technology is really an interesting thing to put into BMS systems…'

Interview C also highlighted the fact that merely having 3D model of building portfolio of the customers have proven very valuable and cited an example of how its saved a customer time and money they would have spent in traveling to physically take measurements of their buildings to enable renovation to be done,

and for example, I had a customer yesterday, who asked me about the 3D models, "can I go into this specific room and measure the height of these windows" and I did that and he said oh that saved me from a trip of 10-15 kilometres. So if you have this kind of data digitized that way you *turn complex data into a visualization that human beings can easily understand. So this is this is again the future…*

(Beetz, et al., 2020) also states notwithstanding these challenges, a successful implementation of the Digital Twin concept has the potential of unlocking economic, social, environmental, and business value in the built asset industry. The Author of this paper to ascertain these value additions explored the benefits derived from the systematic review (use cases) as well as in the interviews into these broad values namely, economic, social, business values.

The table below briefly classifies the benefits derived according to these for main value propositions,

Authors	**Economic**	**Social**	**Business**	**Environmental**
(Küsel, 2020)				
(Lu, et al., 2020)				Enabled detection of anomalies and take preventive actions before severe and catastrophic consequences happen
(Peng, et al., 2020)	Reduction in energy consumption	Increase in management satisfaction	Reduction in faults and requested repairs	Reduction in CO emissions
(White, et al., 2021)		Engaged citizens to get valuable feedback on key urban and planning decisions	Enabled city planners effectively plan for future developments	Enable city planners and citizens adequately prepare for natural disasters
(Lin & Cheung, 2020)	Reduction of operation and maintenance cost			Enabled effective environmental monitoring, including hazardous gas concentration to ensure human safety and comfort
(La Russa & Santagati, 2020)				Ensured the continuity in preventive actions in the absence of qualified professionals or

				monitoring systems
(Lu, et al., 2019)				enhanced environmental monitoring and asset monitoring to keep working environment comfortable
(Xie, et al., 2020)				Enabled automated inspection of indoor environment without excessive intervention from FM
(Heaton & K.Parlikad., 2020)				
(Khajavi, Motlagh, Jaribion, Werner, & Holmstrom, 2019)	Reduction in energy consumption cost			Enabled AC systems to source air from the cooling parts a building outdoor rather than expend energy to cool and recirculate air
(Lu, Xie, Parlikad, Schooling, & Konstantinou, 2020)				
(Lu, et al., 2020)	Reduction in maintenance and repair cost	Enabled environmentally friendly urban planning		Enhanced environmental monitoring and asset monitoring to keep working environment comfortable

The table indicated that despites the challenges in adopting the DT concept, the literature highlights the clear value addition the implementation of the DT concept will provide to the AEC industry and stakeholders.

6.4 Limitations

Certain factors are major hindrances to the adoption of the Digital Twins Concept and achieving the expected values. Some of these limitations are discussed below.

Clients Requirements and Lack of Focus:

End user (Facility Manager/Building Owner/city planners, governments, citizens) of these systems have a major impact on the components of the system. Most end users are not technically inclined to be able to tell what technologies or components of the system is made up, they are often satisfied with the simplest and cheapest systems that will enhance the daily activities. Interview B and C highlighted the fact that most of the client's focus was keeping the maintenance records updated and as such very few clients use the other modules of the systems like energy optimisation module, while others are also satisfied with just viewing pdf drawings. This however is changing due to the technological advancements and increased client's sophistication.

The lack of focus is also partly due to the nature of operation and maintenance activities. Interview A highlighted that only 20% of their daily activities is done digitally and 80% involves relying on the expertise and knowledge of technical professionals. Very little investment is therefore made in the digital technologies therefore in the Operations and maintenance phase.

IoT Limitation

While IoT technology was a major component in the development of the digital twin concepts. The interview analysis indicated that there is very little implementation of IoT technology in practice. Even though the advantages which included its wireless connectivity, cost and its capability to measure more things, there were certain factors contributing to the lack of implementation. The major factor noticed has to do with absence of standards to guide the use of these IoT technologies or building regulations that requires all electrical or data connection be wired instead of wireless.

Another limitation was notice during the literature analysis was interference in the communication between the sensors in the network of WSN enabled IoT technology. This will impact on the quality of data from the IoT sensors and as such efforts must be put in to ensure quality of the data from IoT technology/sensors before they are widely adopted.

Lack of standards

This research noted that there are no specific standards that relates to the development of Digital twins in the AEC industry. BIM standards are specific each of the lifecycle phases including **PAS 1192-3** which is specific to the Operation and Maintenance phase. The problem with **PS 1192-3** is that it was created in isolation without organisational processes and asset management processes and as such limited in the development of DTs. Another standard related to the operation and maintenance phase is the **ISO 55000:2014**, Asset Information Standards which focuses on developing an asset management system for an asset centric organisation. This however lack incorporating with BIM standard and leads limited use of BIM in the O&M phase.

Efforts must be made to align PAS 1192-3 TO ISO 55000:2014 to aid in the development and adopt of the Digital Twin Concepts.

7 Conclusion/Recommendations

In conclusion this study was aimed at answering the problem formulation and its subsequent sub questions namely,

How can digital building twin concept add value to the various stakeholders during the operation and maintenance phase of the lifecycle of the building?

- What is the status of digitization in the operation and maintenance phase of building?
- What does the digital twin concept entail?
- What value can it provide to the various stakeholders involved?

According to the research design the problem formation were grouped into three main broad topics and were answered based on both the systematic literature review and interviews conducted with industry professional. Before answering the question, the author briefly discussed the historical background of the Digital twin concept and its application in other industries mainly the manufacturing industry. The fourth industrial revolution which led to the broad application of the Digital twin concepts as well as other digital technologies including IoT, Cyber Physical Systems, etc were also discussed. To have an overview of what pertains in the AEC industry regarding the Digital Twin concept, three main perspectives were discussed,

BuildingSmart which is the industry go to place for developing digital open digital solutions and standards for the built environment recognises the potential the DT concept in unlocking economic, social, environmental, and business value for the built asset industry. They acknowledge that to adopt the DT concept it is essential the shift from the traditional PBOD life cycle to PBO-I which focuses more on use and a broader network of connected systems.

CDBB UK also which is an organisation supported by the UK government consisting of industry, academia, and policy makers to digitise the entire life cycle of built assets by finding innovative ways in delivering more capacity of existing social and economic infrastructure. They have proposed the Gemini principle as guide in development of a National Digital twin (collection of digital twins).

Last but not the least was SPHERE (Service Platform to Host and sharE Residential data) which is a four (4) year EU- funded project (2020), being carried by 19 SMEs, RTOs AND Large enterprises which aims to provide citizens, AEC stakeholders as well as city administrations and urban developers, with an integrated ICT platform that ensure better assessment and developments of Design, Construction, and performance of residential buildings. These three perspectives highlighted the efforts being made in the AEC industry towards the adoption and implementation of the Digital Twin concepts and provided guidelines on how it can be realised. This was also supported by the proposed maturity levels for the development of digital twins by (Evans, et al., 2019).

The systematic literature review highlighted the efforts being done both in academia and industry in implementing the digital twin concept. This included the limitations that existing in the current digitalisation during the operation and maintenance phase of a building life cycle and the situations in which the DT concepts can lead to improvements of the daily operational activities of the stakeholders. It also highlighted the processes involved in developing digital twins including the use of open standards (BIM standards), integrations in common data environments (Navisworks and Autodesk forge API's), enabling technologies (IoT, BAS, Cloud Computing etc), and the benefits derived through the implementations.

The interview with industry players also highlighted what the current digitalisation of operation and maintenance phase of a building lifecycle, including the systems (CMMS, BAS) being used in operation and maintenance. The interview also highlighted the wish list of these industry players whiles at the same time highlighting the major limitations they face.

Based on the analyses of both literature review and interviews the author was able to answer the problem formulations in three mains themes, current state of digitalisation in the Operation and, Maintenance phase of a building's life cycle, the components of the digital twin concept (conceptual framework), and the value additions in implementing the digital twin concept. This research contributes to identifying the added value gained during the implementation if digital twin concepts.

The research ends with highlighting the limitations associated with adopting and implementing the Digital Twin concept and proposes a way forward.

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Appendix 1 Transcribed Interviews

Interview 1

First, we would like to ask you to describe the role you play in a building project during the operation and maintenance phase and how many years have been in the industry and little bit about your professional background?

"Me, Michael is the team leader of Campus Services, and Jan is a Technician."

How does your BMS system work and what are the components of your BMS systems?

"I think I want to start just by saying that we have a building management system, a platform that gives us an overview of all the systems in our buildings, how they perform, their values, their setpoints […] and that is especially heating system, ventilation, cooling, light and a fire alarms. […] These systems we have on most of our buildings. […] We're very pleased to have this system especially in this Corona times where we all sent home because we can actually monitor most of our systems from home. […]

On the front page we have Aalborg, we also have in the same system in in Copenhagen and in Esbjerg where Aalborg University is also located. […] We have an overview here and to the left we have the different areas. […] So, when we click here, we have two at addresses and you guys are sitting on number 23 so let's take that building. So, from the left side we have an overview of all of our ventilation systems, and right next to that we have all our heating systems, and next to that we have the hot water systems, and the next step we can see an overview on each floor, so when clicking on one of the floors you have an overview of the specific floor that you want to see.

Next to that we have the cooling systems, cooling systems for the hydraulic, for some of the ventilation as well, and then we have all different kind of systems, lightning, head windows, sunscreens, compressors […] and the right we have alarms on home systems and some UPS no brake system as well.

And for a technician like Jan or one of his colleagues he also he can on one side, he can click into one of the systems if he wants but he can also see if there is an alarm on one of the systems. And we have prioritized our alarms, so they are critical and less critical alarms and then there are alarms that are stop being an alarm that are back to normal. We can always see what kind of alarms we have and react to that, actually the system gives the technician an SMS or email says "Hi, there's an alarm there's a pump that stopped" then we can go out and check it and make it work again. Jan will show you one of the comfort and ventilation systems. So, when we click on so, that we can actually see all the measures and at most of the other components that are relevant to have data on a ventilation system. We can see where the air comes in and out, and we can see all the values, so we can see what are the temperatures before the heat exchanger, we can see the values, see how fast are the ventilation running, is the heat on is it off, is the cooling on […] we can see the pressure so we can see if it performs well."

And all these data are real time data right now?

"Yes, it is real time data. You can also see the efficiency on the rotator, and if we want, we can also click in on some of the values, for instance, to see how is the temperature evolving: is it going up is it going down, have there been any abnormalities with it and we can put locks on it. The system can't lock everything, like 30 days backwards but if we arrange it, we can say this temperature of this pressure of this pump or whatever we want to lock on that and then it starts looking for until we say it should stop.

We can also click and if we want to change how the system operates, for instance if we want to change the set points for the temperatures, if we want to reset it or if we want to say the ventilation system should always provide fresh air at the temperature of 22 degrees we can set it to that. But if we want to change it so it regulates of how the temperature is outside, we can also do that, it regulates automatically, so if it's very cold outside it gets a bit warmer air and when it's very hot outside, we often want cooler air than it's regulates that automatically. And of course, if anything stops, like the ventilator or something like that stops, we get an alarm on that and that is all kinds of set points and night cooling […] there are many setpoints that we can change."

Both, ventilation and heating, how are they controlled based of course on this real time measurement of the actual conditions in the rooms do you also take into account like prescribing, we know it would be colder tomorrow, so we start turning on the heat or?

"No unfortunately it's not that intelligent. It can only see the real time temperature, we have I think maybe a couple of air stations located on some of the big buildings, and it detects if there's wind and the temperature and then the system reacts and change to that, but if it's if the weather prediction says that it would be very very cold tomorrow, know it before it gets cold, depending on how modern and how new and how much money there was on the building, the buildings at the system are more or less advanced, and more or less intelligent. In a normal study group room you will have a so called IPI zone where a controller controls the heating valve for the radiator and the valves for the ventilation ducts, and if it's if the CO2 level rises it provides more air to the room, if it gets too cold the valve for the radiator opens. […] This is one of the zones for one of the study rooms, here we have room temperature at 20.2 degrees, we have an air quality of 202 ppm on the CO2 level, and the set point right now says that the heat should start when the temperature drops to 19.8 degrees, cooling should start when the temperature gets to 20.8, that sounds a bit strange .[…] That is the value of levels for the panel that the students can change in temperature. Because of the unnormal circumstances due to corona virus many of our set points are not normal, we actually turn down the heat on lot of places and are only heating up where people say that I actually need to go into work here. […] There's a lot of set points like the light levels, at what point of ventilation to start at the high PPMS […] and you can see logs as well on each room, logs of temperature and logs air quality. You can see how the temperature is developed in the last couple days, and the thing that I want to state is that even that we have these systems they are very smart and we can change a lot of things we are often limited to, like, a ventilation systems capacity, so for instance if it's very very hot and everyone is sitting and studying all the rooms are calling for extra air but we don't necessarily have the enough amount of air that is a typical thing on buildings. […]

In heating system heating there are colors of each heating zones, here we see the in and outcoming water to handle certain temperature in on the way to the room. […] This system makes sure that the temperature for the hot water to the radiator is correct and we can change the values we can see how much energy we have been using how many of cubic meters of hot water we have used. That is the speed introduction to our BMS."

I wondered this picture you have, these floor plans you have these for all buildings I assume, so are they made specifically for this system or are they connected? I know you have 3D models of many buildings.

"Are you thinking about the drawings? […] We get the drawings from our facility management system, but it's not put in there automatically. If we want to change 2 rooms, all the drawings we have to put it in manually today. But we don't have like a person who sits and draw them one time more in the building management system just put it in the file and they are imported.

And we have a lot of exchanges of data, like for instance all the energy measurements are being sent from building management system to the energy system, and the fire system when it detects a fire it sends it to the building management system, if you book an auditorium or a seminar room the booking system will tell the building management system "hey the room will be booked at 10:00 o'clock so make sure to start heating it up at 9:00 o'clock" and if it's not booked, all the values are going down to save energy so the ventilation goes down to minimum, the heating goes down a couple of degrees as well.

We normally only have cooling systems and air condition on laboratories, not in offices, and not in study rooms […] and that is because Denmark is historically not a very hot country, but we tend to have more and more heating problems, but we don't want to use that energy on cooling, we want to be more green and sustainable.

I wondered about having overview, of course you have alarms on everything so if the temperature is too high or too low somewhere you get an alarm probably and you could do something, I wondered if you can also have like some kind of manual, I mean you had this drawing again showing one floor of the building?

[…] if we have an alarm on the on the graphic you can see the red bell. […] There is an alarm, because the temperature is wrong than we can reset it if it's too cold. […]"

At beginning you showed us the plan of the whole campus, I just want ask if the BMS for each individual building is connected in a way like for energy purposes, there is an ecosystem that connects all the buildings energy use so you have an overview of how each building is consuming energy? […] there is an ecosystem that connects everything already.

"Yes, well if I understand your question correctly, we don't have within the building management system an energy overview because it's too expensive to buy it with this company. So, we have a separate energy systems where all the data is and there we receive all the energy values, so we can see for instance this building compared to another building is it producing or is it consuming more electricity or less and also per square meters, so it's easier to compare the two buildings and then we can see there's a high level of energy. We can also get an alarm if we see a quick rise in

water consumption etc. We can see that but that is a separate system. We have about, I think between 1200 and maybe 1500 energy measures, so we have a lot of data.”

The plans you used to visualize the operation and the data I wonder whether it's helpful if you have those plans in a 3D visualization, so you view the operation in 3D instead of the plan view?

“We don't have it and I know that the that is a new thing to have but unfortunately, we don't have it today.”

Would it help the visualization or the job if it's in 3D?

“To some point maybe, but the way that things are going we are often just happy to work within the phrase “keep it simple”, because if it gets too advanced it's very expensive to keep it updated, and this is just you're sitting here within like 30 or 50 different buildings, this is just 20% of Jan’s work so he has a lot of other system that he also has to know how to operate. So, there should be a specific purpose to have it in 3D [...] Jan don't see need for that.”

You said it didn't have to predict future performance, for instance if it's going to be very cold tomorrow or in future you can set it up so that it responds to the future building expected performance. If you have this data stored over a period of time you can analyze this data and also able to predict that it’s going to be cold, so can’t you set up the variables and their values so that it responds to unexpected occurrence?

“Jan said that to some degree the heating system actually have that in it, so it looks on the data within the last three or four days and then it predicts how the heating should regulate within the next coming day, so based on outdoor temperature we increase heating. We have actually tried to buy an extension, an extra module to the building management system with the intelligent algorithms, and that system should help the operators because today we have a lot of dates and we have a lot of alarms, but everything is depending on how the operator sets the set points and how involved he is on making sure that everything runs perfectly. And of course, Jan has one way to do it, his colleague is maybe have another way to do it, and therefore we bought this extra version, where algorithms gives you an analysis of all the data within the system and then tells you how to improve it, reducing energy and making better indoor climate and formants in general. Then the examples for this was that the system suddenly gave us a notification saying that “oh we think that there are filters that should be changed so the pressure isn’t that high over the filters”.

But what we discovered is that this is too new and it's not efficient enough. We used a lot of money on buying the module but it is too [...] I’m saying it out loud and idiot can tell us what the intelligent algorithms was explaining to us, and therefore we said thank you, but no thank you, we did a proof of concept but it was not efficient enough, but I definitely think that would be the future, but within a couple of years it would probably be more intelligent and efficient than it was two years ago.

Another thing that we also are interested in is the IoT technology or basically making things not wired, so talking about the wireless. We are often constructing new rooms and buildings, and it's very expensive to have cables and communication between each component, and it is a bit old *school if you ask me. I want to do it wireless, I want to have more IoT, that can measure more things so that we can reduce energy even more, and have better indoor climate, so that is the IoT technology is really an interesting thing to put into BMS systems."*

***S*o then does that mean that the current system sensors you use are not IoT based sensors?**

"Correctly. All Danish standards within the building construction say that everything should be wired and that is because it's very old school thinking, they're not as innovative as they should be, but I think within 2021 we should have a proof of concept project on IoT components within the building management system. Make sure the communications working probably, making sure that the quality of the components are adequate […] and if that is the success than we would probably say that that would be the new standard, so the next time that we change a building or renovate or whatever we will hopefully use wireless components."

So, limitations by the IoT is not being used in Denmark, because you have no standards to regulate it yet?

"I mean, those standards that we are talking about, that points towards wired systems and traditional systems not being very innovative is not from the government, it is not government rules it's just I mean, it's like industry standard so organizations in the industry agreed, like you have with the BIPS, so an industry association, they make their own standards, basically this is how we work […] it's just like the way we work, but we're seeing changes and this is only the beginning of it."

***A*re you able to make report out of the data that the system gathers?**

"Well, we can be exchanged all the data to Excel but it's not like we can auto generate a beautiful report with the dashboards or anything like that, no, but we can exchange all the data. We can also exchange it to other systems, for instance the energy measurements, all the data from energy systems are put into another energy system that can make reports."

***D*o you have the ability to automate some of your controls to respond to faults during operation*?* *S*o did I understood *it* correctly that you don't really have the ability to automate the responses just to some of them, for instance for the CO2 level and the heating?**

"Normally if the CO2 level rises, we don't get an alarm because that's not critical. So, if the CO2 level rises the ventilation system detects that and open the valve so more air goes into the room and then it goes below the level again. We only get an alarm, for instance if the valve malfunctions or if the ventilation malfunction not if the level just rises unless it's critical measurements for instance on a laboratory where you always have to have a temperature within some margin, so we get an alarm when the automatic response does not work."

Interview 2

"I have worked in Norway as a BIM manager for a couple of years, and now I'm in working with Dalux, working with software. this is basically creating software more than creating buildings but it's pretty much the same. We build it from bottom up same with buildings, so creating software is pretty much the same as creating buildings. So what is your general topic, is it just Digital Twins for your thesis or?"

It's about how Digital Twins can add value in operation and maintenance phase of a Buildings lifecycle.

We would like to ask you to describe the role you play in building project during the operation and maintenance phase and how many years have been in the industry and a little bit about your professional background?

"*I work with the municipality of Copenhagen, where this was facility management for a couple of years, where my focus was digitizing our portfolio of buildings. We had 2.5 millions square meters of buildings, and we needed that digitized so we started creating models of all our buildings and measuring them in general, because we didn't have any material, old drawings and stuff like that. Then I worked with Dalux as a consultant/developer on our FM solution as well, so I talked a lot about building owners and a lot of their issues and how they maintain their buildings in general, and then creating solutions for them. Today I'm more involved with the development of our software and it's mainly in our construction part of it, but lot of things overlap regarding where you are in the Phase of the building."*

What building operation system or facility management system that your company works with and how does this system works and what components does it have?

"We create our own facility management software, so we don't use it ourself, we sell it, but it's DaluxFM, it's a solution for building owners and large portfolio managers. *So we focus mainly on, you can say, large scale portfolio owner, so that would be municipalities, we have a lot of municipalities in Denmark. We also have big building owners like hotels [...] so they normally they have from 10 to 1000 buildings in that portfolio, and in our system we try to manage the different aspects of the facility management part. So, when you look into facility management it's not only, even though it has to do with buildings, it's not the same as the construction site, it's something very different. So we have a 3D viewer and we have a lot of functionality, it's based on modules, so we have a module for, or even say tasks (work orders we call them) and we have one for helpdesk, that's the users of the building, how do they say something is wrong with my building, we have something for assets, that would be your components in some way, we can also be linked to objects and so you can link it all together, documents in general, we have a module for that. But how, we can say we connect all of these modules so all that information can flow across and can all be connected but depending on what your resources are that's also where you place yourself in the digital part. Some people buy this system for only using the help desk, for example the Danish police, all of their facility management runs in DaluxFM and that's when their car crash, that's also part of the portfolio, then they report it broken inside of our system, but that's asset management, that's an asset in our system but in their portfolio, as well as their buildings. So, if*

we look at digital twins it can be a lot of things, it can be a placeholder, for placing all your things, but it can also be more advanced depending on how you want to go with it."

So, it's not part of your duty to carry out maintenance of some of the assets?

"We don't, we only create software. We don't do any work inside, we don't do anything on their part, they maintain it themselves. We only create the software and advise them how to use it."

So, the person who uses the software is a client or an organization?

"Yes, they do all the things there but by themselves. We never type in any data into their system they do it by themselves, but we have a lot of customer requests. So, for example we have a booking system so we can see which, if we have somebody who rents hotels so you can imagine you have a 3D building, probably a Revit model or something like that, and you upload it to our system and we have all the rooms inside. And when they book a room, because the normal system they have it's just a list of all the rooms they have, but they want to see, they want to combine our, is this room booked? when did we last have the cleaning here? when is it booked.? So, we do some of these integrations and link them together, so they can add both their, if they use QR codes in these rooms, how are they linked to the booking system, and how is that link to their cleaning and general facility management, which kind of assets do we have inside of this room, which kind of TV, what type of channels do we have on that TV. And we can continue and continue to add this data, but we have a placeholder where we can link all of this together."

So, this integration, is it possible to do it with live data, like real time or it has to be done at certain periods?

"That has something to do with development. So that's how much we allowed them to do, because they can ping our system, that means that they, if they do use our API and they created integration they can send data by, they always do that by an interval. When they create, I don't know how much you're into the development of the software, but you have an API, so we give them features and then they can, for example if they want to push some data into our system, that would be some of the properties in an asset or something like that, in the case where a room is booked and they can decide how often they push it into our system. We set some limitations, because or else they can crash our system if they do it every millisecond and it's the large amount of data, so normally, we set up some limitation for it, but it could be every minute or something like that, they push in new data into our system."

It also because the Digital Twin is a mix of lot of digital technologies, and we could see that your software already has the BIM part of it, it does BIM integration, asset management integration. But the major thing that is missing in the operation and maintenance phase is integration of IoT, real time data. So, our question is to what extent is your system capable of integrating data from IoT Sensors in real time?

"Even though you call it live data, it is always set up like this, so it's always set up to be when something new it pushes data into the system, so it is live data even though it's by an interval, but it's called live data. So, if you have the IoT, some kind of sensors for all different kinds of, even though we use geometry, we split it up in Dalux, even though we have geometry is just a

placeholder, it's just a placeholder where you link this data together. If you use the actual geometry it doesn't have to be in […] that's just one part of all the data that you have. So, geometry is actually a stupid thing to link it to, because it always changes. So, we have done it a bit different in our system, so we have something called assets, because we also cover things that are not a part of geometry, so you don't want to, you don't need an object, a geometrical object for example a television, you need to place some data on this part, you don't need it visualized in 3D, you only need a placeholder, you only need somewhere we can link all this data together. And that's how we try to do it, so if you link 3D geometry to it that's just one part of it, but then you have all the rest and that's how we see this, because you don't need to visualize it in 3D, somethings you do but not all. So, the room is also, you can say even though it's it has some geometry it doesn't need that, it's maybe restricted by some rules, by you can say by walls and ceilings and stuff like that, but you can also have areas. Areas is something different than for example a room. So, it's just to explain how we see this IoT, you select the sensor, could be heating, could be something and you select the way you want to visualize this, in this case if it was heating, would probably be the room, but if you have one sensor or multiple rooms then you would probably combine this and stuff like, but it would be a property connected to the room maybe, in our system or something else."

So, your system has the ability, even though we call it real time data, to update as and when the need arises depending on the users?

"So, you have normally a third-party software. So because you have multiple software depending on where you want to get your data source, you would always rely on these integrations and how you want to set this up, it's always something you have to do and some kind of media you create, so all the time you need to develop this, and that's the good thing about APIs, you can extract data and you can import data. Normally, even though it sounds very easy, but there are always some things you need to, maybe they import it in a different way, we need somewhere to link these, so if they create their data, we need to be able to source this into something. There is always some middle ground between those integrations, where we need to transform some data or something like that. It's really cool when they get it up and running, but it's always piece by piece. There's no solution that covers all. It's because it's always if you look at the use cases, in facility management sometimes that development takes more time than the actual value it gives, and sometimes it makes a lot of sense. That's really up to each client or each user. On a hotel, where you have buildings that are used a lot or the purpose is very different, maybe a school but there are also some similarities, but the use cases is very different."

So, in your opinion which of the use cases do you think it makes more sense to have that system where it is updated frequently?

"It depends on what you want to use it for. It would be cool to have, if you could see all the temperatures and all the rooms in a school, that's a good idea maybe."

We are trying to find out the values it offers to the user, so that's the purpose of our thesis.

"Who is the user?"

So yes, we are trying to look at the stakeholders involved, like from your perspective, and the client's perspective and see how he values certain things and what Digital Twin presents to him.

"I would say that depending on who is the user, I think the perspective is very different, but that would be my take on it. We create software, we see a lot of use cases, but it's very different what the use case are, and it's very difficult if we don't have for each like IoT [...] that can be so many things. So depending on if we don't focus on one part of it, it is very difficult to say what is the value of it, because it depends so much on who are the user of it and what do we want to use it for. It's very difficult if you don't know the end goal and the values of it when we start these projects. We just made integration with client that they have bought our system and they have vacation houses, that they rent out for people and I think they have 300 of those or something like that. It was very difficult for them to see "I need to go there, and I don't know, fix the door, and it was very difficult for them to see, to plan their work day if they didn't have, is there other people in it, is the vacation home booked or not. And that comes from their booking system, and we don't have a booking system in our system. That's a small integration but you can add on to this depending on the use case, and it could also be all the small things and we can [...] Internet of Things, is also some people use drones, they scan their buildings and then they update it directly. It's also not a live coverage but a day-to-day coverage of building portfolio. How much value does it give? It's very hard to say, but it's depending on which portfolio you have. It's very hard to say in such broad terms what is the value because each one of these is its own use case, so I think that would be my take on it. If you look at BMS systems it's pretty much the same. They cover some things and the same, we can show data inside of our system. What is the value of it? You don't need to log in to two systems. Normally that would be the value of it, so depending on you can link it to your 3D geometry, maybe some of it, because it's different data, but it depends on how you like to use it and how much you use it I guess."

In terms of the future, do you think there will be any modification to the system as it is, any addition or any technologies added to it?

"I don't know, you can say if you look at the very broad spectrum, every system uses their own way of integrating to other systems, meaning that when I have some data in Dalux then we expose the data through an API and if somebody wants to extract it then they can connect to our API and extract it, and then put it into their own system. The same way if some people want to push data from another system into our system. They look at their API and extracted through their API and then they push it into our system through our API. But we use some, one way of doing it and they have another way of doing it, but there's no general, you can say there is still a need to be a developer to do this. So, there is no standardization of the way to extract across these integrations between the components that you might have inside of the buildings, and the booking system, for example that's not a building system, so they would never look at this, so we cannot cover it all but it could be some regarding the extraction of data and pushing data from one system to another if you want and also the same with the small sensors in general so if there was a standardized way of doing this it would be easier to build these."

In your opinion what do you think about the DT concept, isn't it like a basis that will form a standard for the extraction and transferring data from one system to another, it forms as a basis for all the data sets and all these other systems will come into the system and extracts the relevant data?

"Maybe, and that's hard to say because it's a bit early, because sometimes you have functionality linked to something, which means that every system have created their own, because not every system is the same, we cannot say that this is the way that you set it up, some people want to add everything into a Revit model, and just put it into properties and just like a fois gra chicken, I don't know, just stuff it, and we have done it a bit different, because we want to split geometry and information about geometry, and we want to distribute to single part of it but all the properties. It's actually very stupid that they are part of the object, I don't know if it's stupid, but it's another way of thinking, but if they start basing this, you also lock yourself according to improvements I would say, because sometimes we want to do a bit better on some parts, and if we are locked into this way of structuring our data that can also be a problem. I don't know if it makes sense. So sometimes, I think it's Digital Twins, I think it's something that would slowly grow into software and I don't think we can do this, I don't think we can make one form for all of it, that would be my guess, never know, maybe somebody creates something generic."

But it also says in the literature, that every Digital Twin has it purpose, so I think, what you are saying it's right, so when you create a Digital Twin, it has to have purpose, So it can't be one for all.

"Yes exactly, that's also one aspect, that is if you look at facility management, that is very important for this to work in general. That is if you look at a construction site, you have maybe 1000 people working on it in total, if you look at a big construction, when you go into facility management, you have three guys working on it and they don't know Revit, they don't know anything about digital parts at all, they call a plumber when something is wrong. Normally in facility management you have no resources for this, so maybe I don't know if you should have, maybe it's something they buy. When they buy a system, for example when they buy our system, we want this this and this add it on and we deliver this for them, but it's not something they have the resources for, and in facility management it's also very different, they use a lot of time on a lot of other stuff in the digital part so, 80% of their work day is something else, they want to grab the low hanging fruits and how do we optimize our workflow today, and sometimes it could be something regarding some form of a digital twin, sometimes it's also something very different."

So, you don't envisage AI, and these other technologies, Machine Learning … etc. making its way into these systems.

"A *lot of potential on that part, because you could add a lot of things and we always also try small stuff, I don't know where you go from good software, good UI and into artificial intelligence and machine learning, it's always some gray area in between, but there could be a lot of potential on that part, but I haven't seen the good use cases in the building industry yet, but I think they could be, it's really hard for me to say, but I think there are a lot of potential. We have worked with the Boston dynamics, I don't know if you know the dog that can run everywhere and we tried in our* *software, but we tried it and so it could go through a building. This was not in facility management, and a part of that we need something, so this dog needs to learn that it can jump over if there is a broom fallen down or something like that, but it is something, I don't know if it's something that goes into our software, but we rely on it. But there are a lot of potential, but I think it would be maybe something else, I don't know, it could also be a lot of the difficult parts in if you look at facility management, it is keeping your geometry updated in general, so there could be some potential also there, but I don't know if you would call it artificial intelligence or machine learning or anything like that but some kind of atomization."*

What in your opinion is the limitation of implementing these technologies?

"I don't think there's any limitations at the moment, but it's just if you look at resources versus value, then I would say it takes a lot of man hours to set this up and even not only setting it up, but also maintaining is something, sometimes you forget when you have a software you also need to maintain it, and maintaining software takes a lot of effort. It's not only just creating it once and then it works, you need to maintain it all the time. So, a lot can be done, but it's always value versus resources and man hours in general."

You mentioned that it was part of your experience being in charge of digitizing an infrastructure of a municipality.

"*Yeah, there was a building portfolio that needed to be digitalized, and we had no idea how many square meters we have so we had to basically creating models of all the buildings."*

Did you use scanning as a part of your processes to get all these digital models?

"Yes, there was scanning and then we had five guys or something and I was a manager on it. They were sitting with the models and creating models and so they went on site into the buildings, scanned them, went back to the office, started the modeling and all of their Revit models, uploading them and then we have those inside of our system. That was basically it. Then we have the rooms, but the problem was, it's always how much do you want to register when you're out there. So floor type, for example we don't have that on any buildings, do we need to?. There was one of the things we took with us, but how much should they register when they were there, because every time you add something new you also add a lot of time, so we set the bar quite low, but we had the placeholders."

And these old buildings, that didn't have the plans, did they have a form of an automate building control system already or the process led to the automation of it?

"No, it was very limited. so no, not that much, so we tried to set up, but no. I don't know if they have anything today."

This is also part of the digitalization process, that we are discussing in out thesis.

Interview 3

We would like to ask you to describe the role you play in building project during the operation and maintenance phase and how many years have been in the industry and a little bit about your professional background?

"I have two roles in NTI, I'm what we call a product owner and in our agile processes regarding development of products to the FM market in Denmark, and that is our NTI-FM facility management software and it's our software for digital hand over for projects to the FM system and that is the 2 main product that we have in my Department regarding the FM systems. My second role is that I'm team leader of the consultants and engineers that implement this software today at or costumers in Denmark, and that's my 2 roles in NTI."

We would like to ask you to describe the NTI-FM system, and how does this system works and what components does it have?

"That was exactly why I send you this document as well, because this can be a big presentation so I sent you like a brief description and summary of the system, so you can have a you have a good time to look into the details but mainly we have an agile FM system which is used by building owners and in Denmark there are some really large customers, like the municipality of Copenhagen, the municipality of Aalborg, and we also have building owners in Copenhagen with 57000 apartments, which is called DAB, so there are some large customers and there are small customers. This NTI-FM system is a broad system which can support functions like helpdesk on buildings, task and resource management, calendar systems and day-to-day tasks of service employers on site and with integrations to drawings at 3D or 2D drawings. Also it's suspected that you gather data regarding your buildings in one system so if you could you go to, for example the municipality of Copenhagen, they have all their buildings in our system, and this is the main system where they have all the buildings and then integrations from there to other systems. So we collect all the data surrounding the buildings or connected to the buildings in NTI-FM with integrations to ERP systems and some organizational systems etc."

You said that you have all the data, does it include data about the performance of the building as in real time?

"No, it doesn't. We are working with a few companies that are developing in this area and if we're doing like IoT sensors and real time data, you must have an IoT hub in front of our system so, for example what we are working with it is called an Azure IoT Hub to gather all this real time data, and you have the assets in our system and you connect that to the IoT hub and then from the IoT hub you are able to identify patterns when some specific intervals are over written and then you can create an alarm or a task into the FM system to the service provider to go check the pump for example. In regards to the question I can sense that you ask if we have that in our system, and we don't and I don't think in general that the FM systems have that Hub, I think they use integration to other cloud computing at IBM or Microsoft IoT hub or any other."

Okay, so the FM systems has to be integrated with these?

"Yes, but these Hubs are big standard systems."

And also the visualization of the whole so for instance, the Copenhagen municipality, is the visualization of the municipality is done in 2D or 3D viewer or how do you do the visualization?

"I don't think I understood the questions."

So Copenhagen has a lot of buildings that you are supposed to manage for them, so the data that you have in this building goes into the BIM model that you have. Are they connected in a way that you could see all the properties that this costumer of yours have?

"Yes."

And is it in a 3D view or, because I can see that it is integrated with the GIS location.

"Yes, it's more complex than that I think, you have all your estates and all your estates are placed on the map like you like Google Maps so you can for example open any of the FM systems and get an overview, where is my locations, and then your estates is divided into one or more buildings. These buildings they have 2D plans or 3D drawings for example so when you look up a building inside the FM system […] you look up a building and you can see in building what data does it have from our system what is stated from the 3D models and so on and this is a form of centralization of the data and so you all this task management is inside our system and we have information on the assets inside our systems and what data is from the 3D models etc. and this is a form of centralization of the data, so all this task management is in our system and we have information on the assets inside our system, and on the side you can see the 3D model and watch, OK this is the ventilation system that if is there's any ventilation system brought into the 3D models you can view that, and they've got all the information as well.'

The data that you collect do you are you able to use it to predict the future performance of some of these assets?

"If you by that you mean sensors and stuff, do you mean that?"

You have data form various sources, some from sensors some from others, and for warranty period and when they are supposed to be maintained and stuff. and we are wondering if this data could be used.

"That is one of the premises our system. We developed something called 10 or 30 year plans, where you can predict what the maintenance costs of the building is 30 years ahead, and that is done by visual, so people like us, go and watch the buildings and put it in the end in the system, and we are right now developing that we can connect it to what we know as predictive maintenance, which is not implemented in very many places yet, where predictive maintenance is using sensors to automatically maintains this maintenance plans and I don't think that anyone in Denmark is at this moment, but I think some of the big building owners is going there and some of the private building owners might be there now but the public building owners are not there yet. This is my understanding, but I'm not sure. But this is coming, this is the future."

Yes, but your system it has ability to remotely monitor with these assets and stuff, so you can access the system from like home. So do *you currently have the ability to detect faults and predict maintenance schedule through Building Management Systems (BMS)?*

"If you mean by the IoT sensors, then no at this moment. We are working to develop this with a few key customers, so this is something that in the near future."

What is your opinion about the limitation of IoT implementation in practice? Because there are lot of literature about IoT and so far we haven't actually interviewed somebody who's implementing IoT technology.

"We actually had one customer actually in Aalborg, Sparnord, the bank. In all of their departments in Denmark they have put the meters for water, heating and electricity and that is collected in a server at Sparnord, and then sent to us, so you can watch the data. So some of them is working on it in some degree but not to maintain their maintenance plans automatically, so to some degree some are doing it today, but this project that we're doing with a customer is to be able to create tasks automatically to send them to us in the system, that something is wrong with that ventilation system and one of you need to do this and this, and right now it's based on the people putting in tasks to the system manually. And I think one of the things that the problem is digitalization, some of these building owners don't have all the data registered, it is on paper. so I think that is one of the biggest problems is that our customers, most of them don't have this data registered in the system and some does."

It's because our thesis is about Digital Twins and it involves a lot of other technologies that are integrated to enjoy benefits so we would like to ask to what extent are you using some of these technologies? And we could tell that you have a BIM integration in your system that you could use for space management, and you are briefly talking about IoT. But is AI and machine learning is also very fluffy. So what is your opinion on this?

"My opinion is that machine learning is a buzz word right now, and I mean machine learning that is a very complex things to talk about, and this is something if you talk about machine learning outside building industry, this is usually something that you employ data scientists and so on to work with, I mean it requires a lot of resources at the moment, and this resources is I think that our segment is already prioritized lower than for example working with the ERP systems and so on, so I think the main focus is right now to digitalize all or buildings into 3D and into FM systems and at some point this machine learning and AI will come to us, but I think that it's often misunderstood what is actually, what machine learning is, I mean I had a customer two weeks ago that said to me "oh do you do you have machine learning in your systems? We want to put up some assets and then put in a few values and written when that value is exceeded, you need to create a task for the maintenance plan. And that is in my opinion is not machine learning. But that's not machine learning and AI, AI and machine learning is that some cloud computing is able to identify patterns in your data and it suggest things that need to happen and I think there's a I think the industry to my knowledge not there yet, but I mean the digitalization is going very very fast this moment so it's a matter of time before the it's there. So we are working in that direction to digitize

buildings and to be ready for it. We actually have developers employed who has knowledge to machine learning."

We could see that the component of your system is energy optimization. So we need to find out what kind of data you get for this energy optimization, so what are the source of data that you use?

"It is consumption of water, heating and electricity. I mean the customers have the meters and then they have another system to gather all the data from all the meters and from there into our system. So again, they have a Hub before and the data our system is to have the data, what is the consumption of our building in a higher level, not in a minute and not in real time but what are these building used energy in the 12 months and you can benchmark that through other buildings in our system. And you have the ability to calculate listen to CO2 consumption of buildings as well, so you can look at the buildings and how much CO2 is these buildings consuming and because we have the drawings you can do that per square meter, so we use the drawings as well and that's something that is unique to our systems regarding some of the Hubs that combined this consumption data with square meters from these drawings."

In your opinion what are the limitations to digitizing this part of the building operation so what is limiting the user of these digital technologies to the benefits of both users?

"I don't know, maybe lack of focus, I mean it seems to be a bigger prioritized to keeping your maintenance plan updated for example. I think it's like 20% of our customers that use the energy module so, some of them don't even have focus there or maybe they have other system, I don't know."

And the User Interface of your program, does it provide results in a structured way to the user like does it different formats that it presents the data, so it becomes easier for the user to understand?

"Yes, for example we have the geographical maps, 3D models and it is structured in a user friendly way, we have apps, mobile apps to display some of the information to the, you know, we have some users don't even know the web applications, they only use mobile applications on site for example, because they have just the information they need, so that my answer would be yes."

We also want to find out which part of your system is the most likely used by the costumers?

"It is by far the task and resource management and that is because this is used to maintain the buildings in a very detailed way, so for example if you go to this building owner, DAB, they have 505 hundred users a day that complete tasks in the system. So this is by far the most used part of our system, if you count by users."

Lastly, I want to ask you about what is your general impression about the Digital Twin technology, that is been mentioned in the industry now?

"I think it's the future, because the complexity of this data is increasing dramatically and it is easier for a human beings to identify objects by looking at it in 3D then looking at lists and mobile applications and so on, so just the identification of the building, which building this is, and for

example I had a customer yesterday, who asked me about the 3D modes, "can I go into this specific room and measure the height of these windows" and I did that and he said oh that saved me from a trip of 10-15 kilometres. So if you have this kind of data digitized that way you turn complex data into a visualization that human beings can easily understand. So this is this is again the future, and we have some customers with object 15,000 building models in the FM system so I mean, something that is often overseen is the maintenance of these building models. You have to have a governance policy process to maintain these data, and this is probably one of the hurdles, so if you were as a building owner what this level of degree, you have to be clear that you need the manpower to maintenance or the money to maintain it. So I think in the municipality of Copenhagen they have around 5,000 Revit models to the buildings and they have six employees, that's doing nothing but the maintenance of this, and this is only used for space management, so I mean this is the future but I think that this is, in order to maintain any data on an object level this is highly time consuming and this needs to be decentralized to all the people that don't work with drawings on a daily basis.'

Another thing that come up so far is that most the system user tend to be large scale portfolio, so they need to have a lot of buildings in the portfolio before using this systems, so is there any reason for that?

"No, we have customers with 300 apartments as well, which is a small scale, I mean it's also scalable under 10 users, and the price structure is divided into 12 steps, so the price is scalable as well and it's scalable to either a number of apartments or square meters.

What would you like see in the future in building operation systems?

"That is hard to answer without revealing my plans, because I decide for myself. The thing is that in our road map for this year this is integrations to public data and it is a new module for outdoor management. I think the FM systems in Denmark has been strong inside buildings for a number of years but nothing outside the buildings, so we are expanding on this GIS, geographical maps. The possibility is out there to be better outside the buildings and this is like drones and stuff that you can put that put that in the system as well, it is like there's like a pending through the 3D models of the buildings just outside and it's better use of objects and takeoffs from the 3D model. So that is in the roadmap this year, so integrations and some functions need to be better at this moment, and then for the start of next year at this moment, but this this can change, it is IoT and it is integrations to what called BIM360, if you know that product from Autodesk. I work with NTI-FM, but my company, NTI, is the biggest reseller, the 5th biggest reseller of Autodesk products in Europe so and I think you have like 90% of the market in Denmark as well, so we have consultants that is exposed in Revit, AutoCAD and 360 and so on. But I work in the development department […] so there need to be a market and customer for it, so efficiency, there is a market for IoT, so we can put our developments to develop something."

Appendix 2 Supporting Images

Figure 22 3D visualisation of AS IS condition of energy consumption data

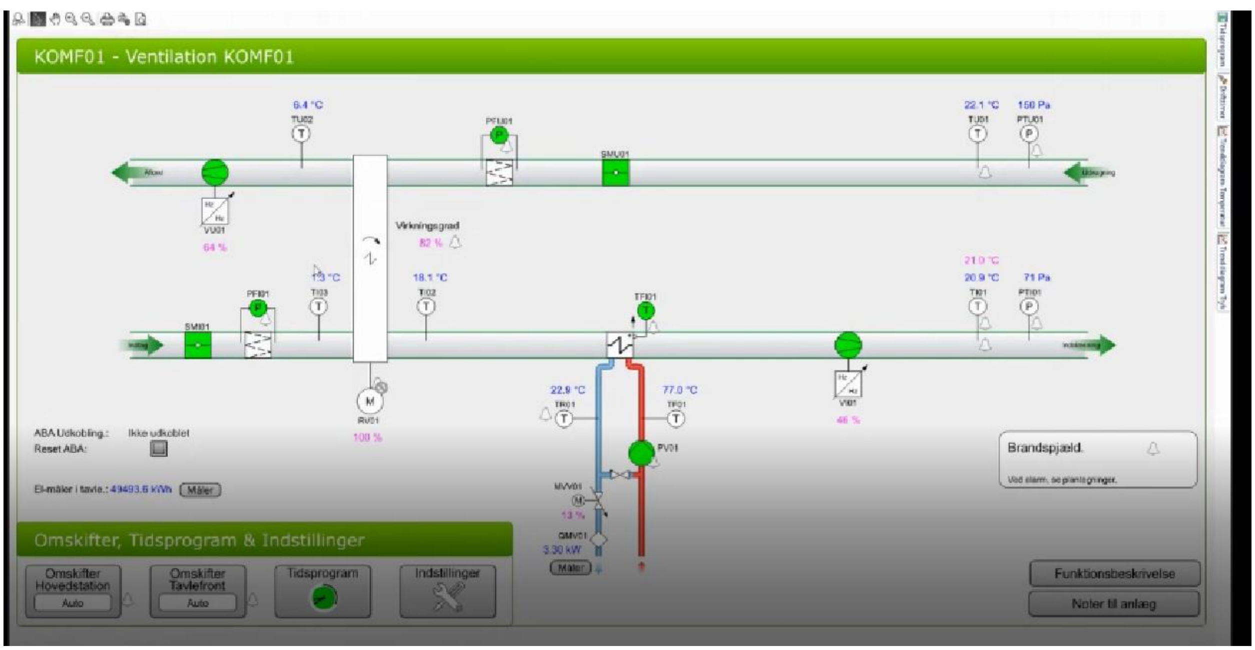


Figure 23 Current Visualisation of as is condition of ventilation systems

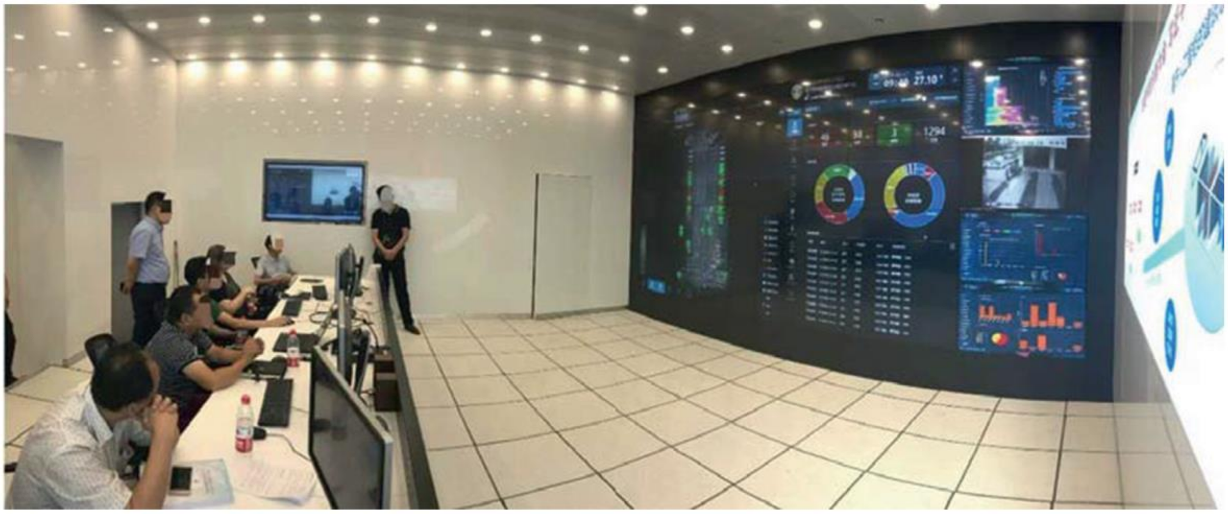


Figure 24 Example of a Digital Twin Technology being used to monitor operations of a hospital

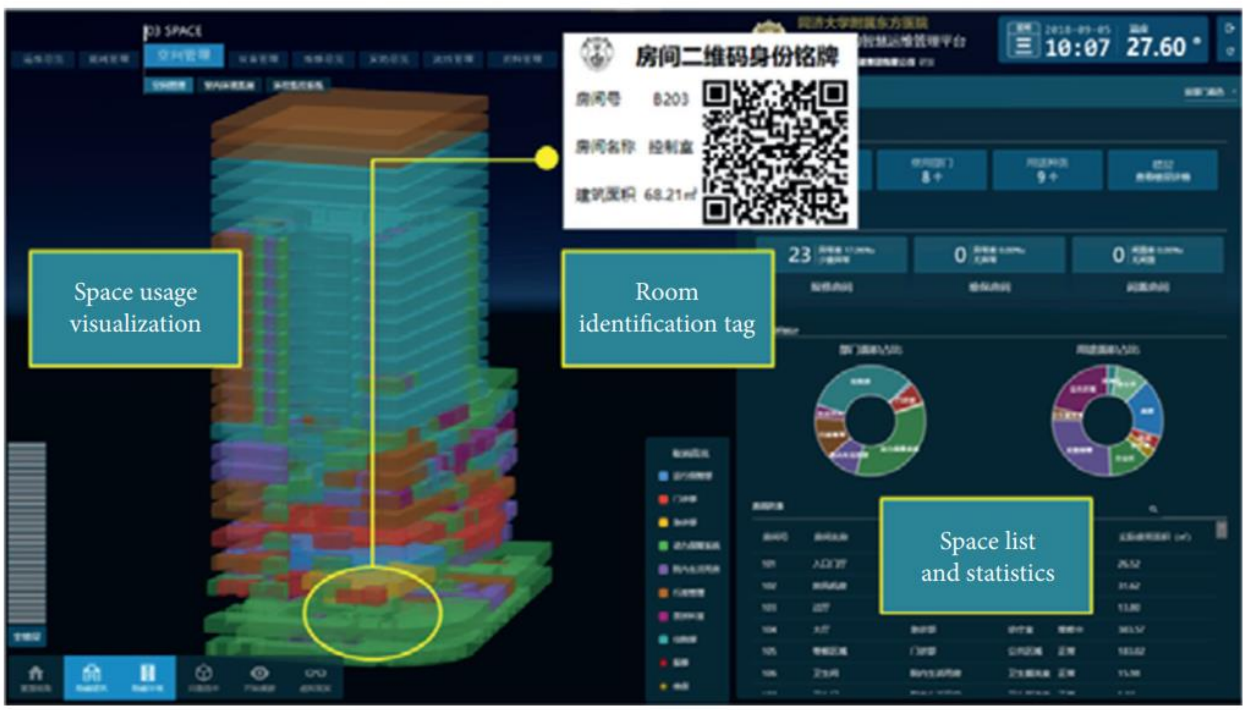


Figure 25 Real time space utilisation visualisation with a DT platform

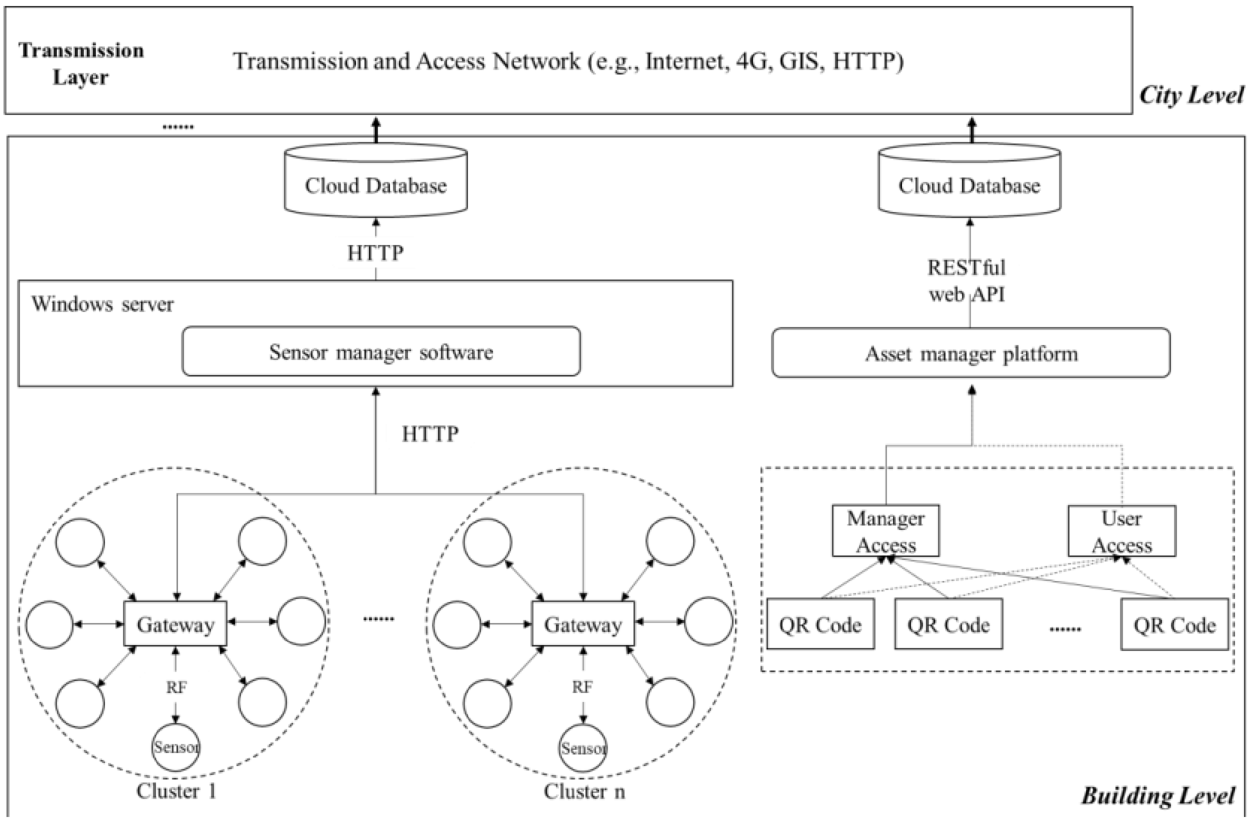


Figure 26 Framework for integrating IoT network with AMS

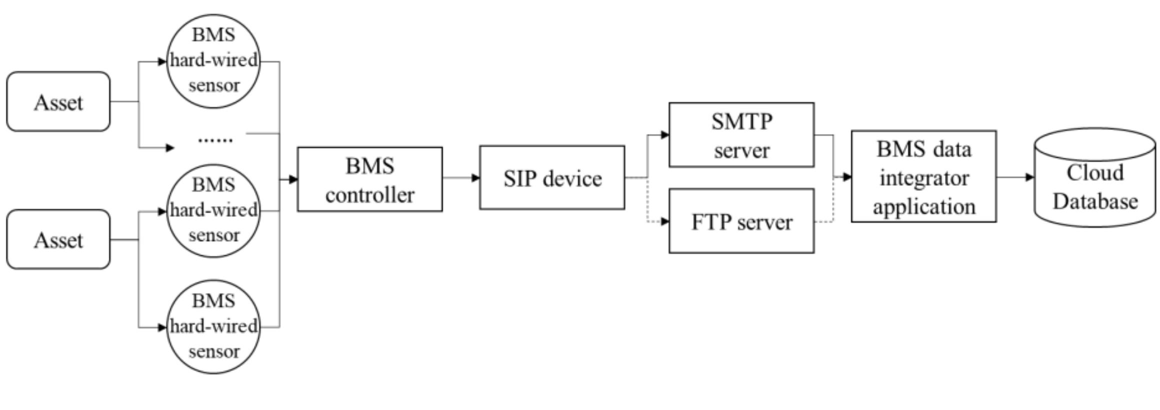


Figure 27 Frame for ETL process for data extraction from various systems

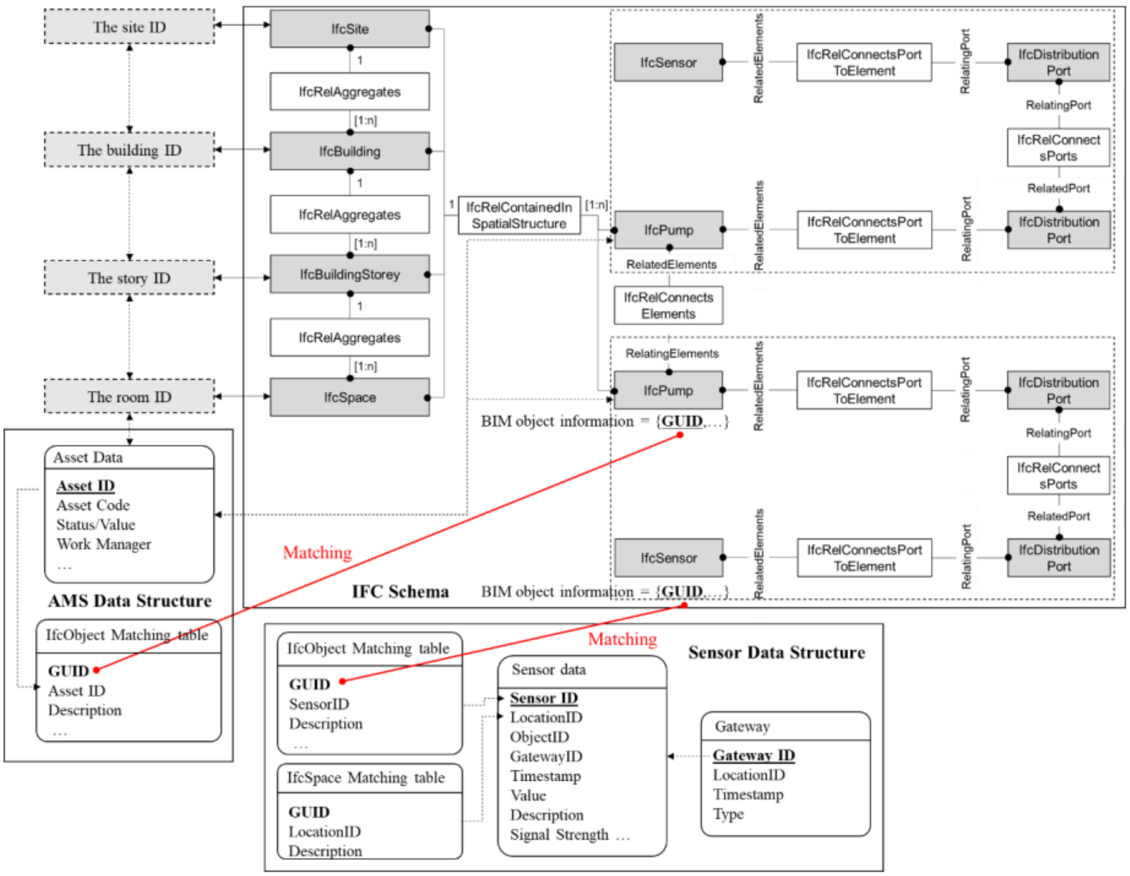


Figure 28 Matching data through GUID

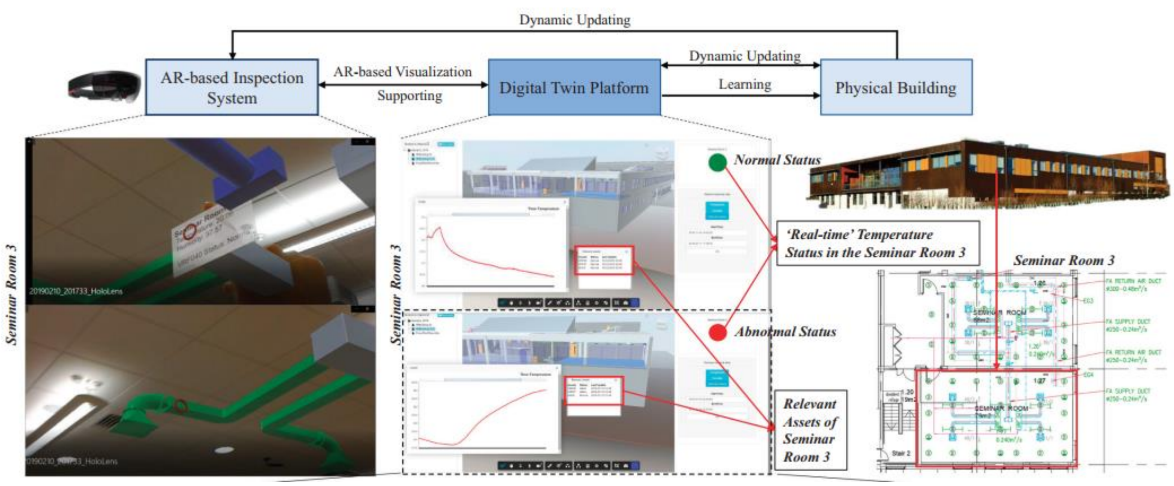
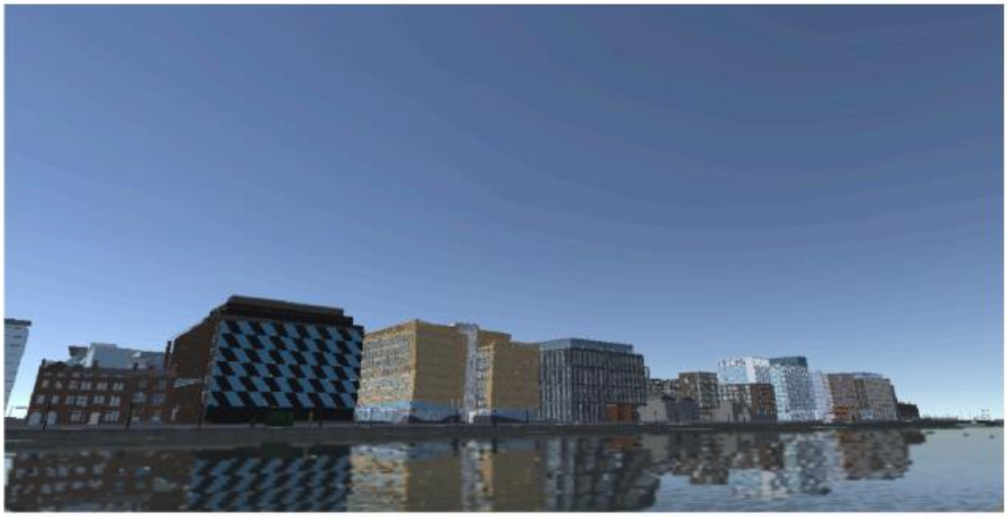
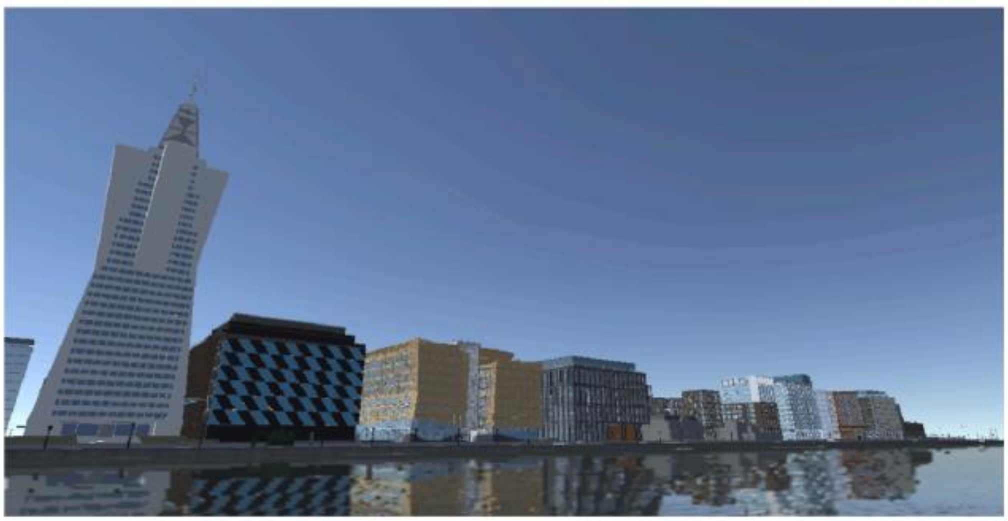


Figure 29 AR Visualisation framework for DT



(a) Current Digital Twin



(b) Proposed Buiding Digital Twin

Table 4 List of shortlisted articles used for systematic review

Author/Year	**Title**
(Küsel, 2020)	Model-Based System Engineering for Life Cycle Development of Digital Twins of Real Estate
(Lu, et al., 2020)	Digital twin-enabled anomaly detection for built asset monitoring in operation and maintenance
(Peng, et al., 2020)	Digital Twin Hospital Buildings: An Exemplary Case Study through Continuous Lifecycle Integration
(White, et al., 2021)	A digital twin smart city for citizen feedback
(Lin & Cheung, 2020)	Developing WSN/BIM-Based Environmental Monitoring Management System for Parking Garages in Smart Cities
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(Lu, et al., 2019)	Developing a dynamic digital twin at a building level: Using Cambridge campus as case study
(Xie, et al., 2020)	Visualised inspection system for monitoring environmental anomalies during daily operation and maintenance
(Heaton & K.Parlikad., 2020)	Asset Information Model to support the adoption of a Digital Twin: West Cambridge case study∗∗This research is supported by the Engineering and Physical Sciences Research Council and Costain plc through an Industrial CASE studentship
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