Univerza *v Ljubljani*
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THEORETICAL APPLICATION OF FRAMEWORK FOR DIGITAL TWIN FOR OPERATION AND MAINTENANCE PHASE

MASTER THESIS

SECOND CYCLE MASTER STUDY PROGRAMME BUILDING INFORMATION MODELLING – BIM A+

Ljubljana, 2022

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BIBLIOGRAFSKO – DOKUMENTACIJSKA STRAN IN IZVLEČEK

UDK: 004.946.5:69-5(043.3)

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Naslov: Teoretična aplikacija ogrodja za digitalni dvojček za fazo obratovanja in vzdrževanja

Tip dokumenta: Magistrsko delo

Obseg in oprema: 100 str., 61 sl., 12 preg., 3 pril.

Ključne besede: digitalni dvojček, okvir za implementacijo, faza obratovanja in vzdrževanja

Izvleček:

Stopnje sprejemanja konceptov in tehnologij digitalnega dvojčka (angl. DT - Digital Twin) v arhitekturi, iženirstvu in gradbeništvu (AEC) so se znatno povečale v celotnem življenjskem ciklu projekta od dobave do faze delovanja in vzdrževanja (angl. O&M - Operation and Maintance). To je posledica potencialnih in dokazanih koristi DT za izboljšanje učinkovitosti in produktivnosti upravljanja sredstev, zlasti med fazo O&M.

Empirični dokazi kažejo, da koncepti in tehnologije DT omogočajo pametno upravljanje fizičnih sredstev, če se izvede integracijo vseh ključnih podatkov O&M, ki prikazujejo statuss sredstev v realnem času. Vendar pa zaradi pomanjkanja smernic in standardnih postopkov za DT ni moč v celoti izkoristiti potenciala tehnologij DT za upravljanje in vzdrževanje O&M. Ob upoštevanju te ovire to raziskovalno delo presoja in analizira najsodobnejše tehnologije DT v okviru podrobnega prelgeda literature v kombinaciji s študijami primerov in demonstracijami okvirnih aplikacij z uporabo programske opreme/platform DT (Dalux FM).

Cilj te raziskovalne študije je oblikovati in predlagati optimalno raven okvira DT, ki se se lahko uporablja v fazi obratovanja in vzdrževanja O&M. Predstavljeni okvir DT vzpostavlja tudi jasen postopek izvajanja teoretičnega DT med fazo delovanja in vzdrževanja, ki lahko vodi do inovativnega upravljanja osnovnih fizičnih sredstev.

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BIBLIOGRAPHIC– DOKUMENTALISTIC INFORMATION AND ABSTRACT

UDC: 004.946.5:69-5(043.3)

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Supervisor: Assist. Prof. Tomo Cerovšek, Ph.D.

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Title: Theoretical application of framework for Digital twin for operation and maintenance phase

Document type: Master Thesis

Scope and tools: 100p., 61 fig., 12 tab., 3 ann.

Keywords: Digital twin, framework implementation, operation, and maintenance phase

Abstract:

The adoption rates of digital twin (DT) concepts and technologies in the architecture, engineering, and construction (AEC) sectors have significantly risen throughout the project lifecycle from the delivery to the operation and maintenance (O&M) phase. This is due to the potential and proven benefits of DT technologies to improve the efficiency and productivity of asset management, particularly during the O&M phase.

The empirical evidence shows that DT concepts and technologies enable smart asset management by integrating all the O&M data to provide the real-time status of the assets. However, due to a lack of guidance and standard processes for DT implementation, the AEC industry is not able to fully leverage the potential of DT technologies for asset management during the O&M phase. Considering this barrier, this research work evaluates and analyses the state-of-the-art DT technologies through literature analysis combined with case studies and demonstrations of framework applications using the DT software/platforms (Dalux FM).

The objective of this research study is to design and propose the optimum level of DT framework applicable during the O&M phase. The presented DT framework also establishes the clear process of Theoretical DT implementation during the operation and maintenance phase that may lead to innovative smart asset management.

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ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my main research supervisor Dr. Professor Tomo Cerovšek for providing unwavering support and guidance throughout my dissertation period. Your deep and invaluable subject knowledge, experience, and expertise have immensely helped me to accomplish this thesis work.

My next heartfelt gratitude is extended to my second supervisor Mrs. Ekaterina Moskvina and her team from the partner institution (M/s Protim) for collaborating with this thesis development. Your association has helped me to get access to industry expertise and resources (IFC and BIM models). I will remain indebted for the support rendered to me whenever sought.

My sincere appreciation is also extended to BIM A+ and all individuals associated with this study program, especially Prof Miguel Azenha and Dr Jose Granja for their valuable support.

Finally, my heartfelt special thanks go to my parent, wife, and children who have always sacrificed their comfort to support my endeavor to learn new knowledge.

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LIST OF ACRONYMS AND ABBREVIATIONS

AEC	Architecture engineering and construction
BIM	Building Information Modelling
DT	Digital Twin
O&M	Operation & Maintenance
FM	Facility Management
LION	Level of information need
LOD	Level of development
CMMS	Computerized maintenance management systems
AMS	Asset managemant system
IOT	Internet of things
AI	Artificial intelligence
ML	Machine learning
IMM	Institute of asset management
Cobie	Construction operation building information exchange
CAD	Computer-aided design
AR	Augmented reality
VR	Virtual reality
CDBB	Centre for Digital Built Britain
NDT	National digital twin
AIM	Asset information model
AM	Asset management
IFC	Industry foundation class
bsi	Building smart initiatives
CDE	Common Data Environment
IMF	Information management framework
AWS	Amazon web service

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1 INTRODUCTION

The Era of Industry 4.0 has brought significant progress in innovation and technology forefront, enabling the wide spectrum of industries to embrace digital technologies such as digital twin concepts to improve productivity and competitive advantage through its process enhancement. Ushering into industry 4.0 has promised significant value in terms of digital solutions that have never been possible prior to the advent of connected, smart technologies (Deloitte, 2020). The digital twin concepts allow the industry to maintain the complete digital footprint of the product throughout its lifecycle and most importantly achieve customer requirements/satisfactions through the realization of customized products, improved operation, and maintenance, reducing the rework and defects, solving the physical problem faster through early detections, predict an outcome with higher accuracy and ultimately achieving the better service and cost optimization to the customer (Adriaanse, Arjen et al., 2021)

The adoption of digital technologies in the architecture, engineering & construction (AEC) sector has been slow mainly attributable to the nature of construction activities and a high degree of fragmentation within the AEC industry. However, with the increasing adoption of Building Information Modelling (BIM) by the AEC sectors, effective coordination among the fragmented stakeholders becomes possible due to BIM acting as the central repository for collating digital information about a project. The benefits of BIM adoption in the design and delivery phase have already been proven and widely practiced. However, the BIM adoption in the asset management areas during the operation and maintenance (O&M) phase has been limited. According to (Boje et al., 2020), This is partly due to the lack of awareness of BIM capabilities in facility management, poor data integration between BIM and IoT technologies, and also interoperability issues associated with legacy formats of BIM. Another researcher, (Lu et al., 2020a) cited the misalignment and complexity of the asset management framework with the BIM information management system. (Adriaanse, Arjen et al., 2021) stressed that, intensive use of advanced digital solutions is the only way to increase the productivity of the sector to innovate much faster. BIM implementation has set the initial step/environment toward digitalization of the AEC sectors by enabling visualization, coordination, simulation, optimization, and the ability to manage some degree of semantic data (Quaye, G.M, 2021). The possibilities of BIM integrations with other computing environments such as the internet of things (IoT), artificial intelligence (AI), and machine learning (ML) have the abilities to improve predictability, enhance decision making through real-time collaboration and enhance information flow throughout the project life cycle, optimize energy consumptions, improve hazard and risk mitigation, etc. (Quaye, G.M, 2021) (Maskuriy, et al., 2019).

The most simplistic definition of a digital twin (DT) is defined as " a digital replica of a real-world entity connected by bidirectional information and data flow" (Opoku et al., 2022). DT is fundamentally referred to as a concept driven by sets of technologies such as artificial intelligence, machine learning, and data analytics and creates digital shadows that can provide insight and learning to the physical counterpart. (Lu et al., 2020a). Unlike BIM, DT has the capabilities to pull the data from heterogeneous sources to perform data analytics such as prior scenario simulations on the test bed before the installation of a physical asset and verify the as-built conditions.

The focus of the thesis is to conduct a comprehensive digital twin state-of-the-art review in the area of BIM-enabled asset management during the O&M phase, review the standards, good practice, and framework applied for the DT application in the O&M phase, and conduct the case study on the thematic area using the available platforms and software applications. The final goal of this study is to propose an adequate level of DT framework for implementing the DT concepts and technologies for the O&M phase.

1.1 Problem Statement

BIM adoption is largely confined to the delivery phase of the project which acts as the central repository for collating digital information about a project. However, its associated benefits and capabilities in the asset operation and maintenance phase is still limited and seen as evolving profile (Quaye, G.M, 2021). The reason for the limitations of BIM asset management maturity is attributable to reasons such as the legacy format of BIM, and the interoperability issue. The digital twin concepts have brought many capabilities to enhance the limitations posed by the current BIM asset management process.

BIM-enabled asset management requires asset-related data to be collected during the design construction phase for the intended purpose of the facility management goal envisioned. This is mainly done using the Cobie process (construction operation building information exchange format). This asset data are further transferred to various Facility Management (FM) information systems, such as EMS (energy management systems), CMMS (computerized maintenance management systems), BAS (building automation systems), EDMS (electronic document management systems), (Halmetoja and Lepkova, 2022). However, these systems lack the interoperability and visualization capabilities required for smart asset management.

The goal of this thesis is to investigate the state-of-the-art asset management process using the BIM digital twin framework to improve the performance of asset management by evaluating each aspect of the asset management realm classified under technology-related issues, information-related issues, and organization-related issues. This evaluation shall be further aligned to international asset management standards -55000 and other regional best practices of Gemini Principal developed by digitally built Britain (dBB), CDBB. The ultimate goal is to develop a digital twin framework with the right level of information requirements and level of details/development for the practical application of digital twins in the operation and maintenance phases.

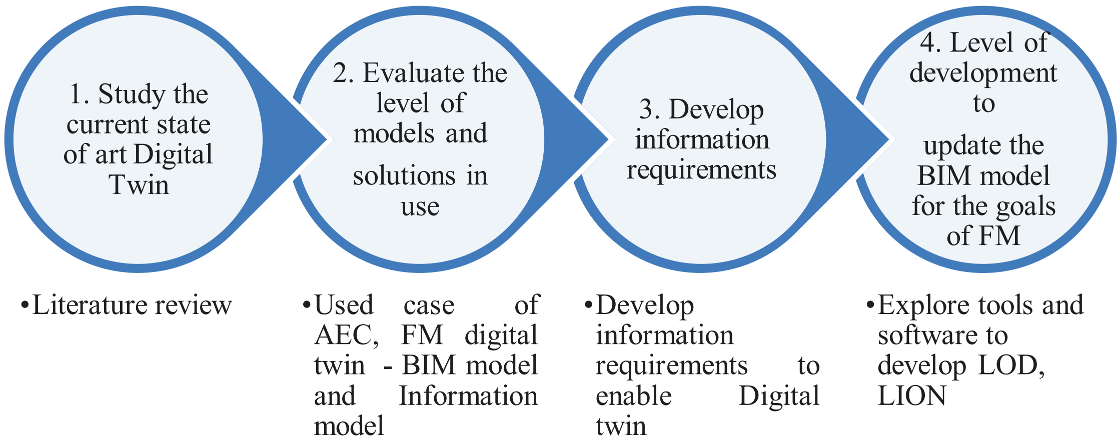


Figure 1. Workflow procedure for Dissertation (Own Work)

2 DEFINITION OF DIGITAL TWIN

2.1 Historical Overview of Digital Twin

According to (Pronost et al., 2021), The first trace of digital twins dates back to between 1967 and 1972 when NASA launched the first Appolo 13 mission. Based on the historical record, NASA engineers built a replica of spacecraft on Earth to train the astronaut in a simulated environment before the mission to predict the different probable scenarios of the flight and finally find out the solutions to solve the problem remotely in case it happened. With the mirrored physical model and simulated environment, NASA was able to safely land the crippled spacecraft using a physical model solution when the spacecraft faced an emergency battery failure. This twin concept, applied by NASA, is the first evidence that a physical object provides information to its virtual counterpart. However, according to (van der Valk et al., 2020), no real connection was made between digital representations and the physical object. The separate physical object was stationed on the ground simulated by the digital environment to stimulate solution in the event of a problem faced by the spacecraft and transmit the solution to the astronaut for manual application. Thus, the direct connections between the physical object and its digital representations have not been achieved (Pronost et al., 2021).

PLM concepts were proposed by Dr. Michael Grieves at the University of Michigan (2003) as the equivalent of virtual digital representations for physical products (Hu et al. al., 2021). This model was described as a" Mirrored spaced model" instead of on digital twin (DT) (Pronost et al., 2021). The PLM model comprises both an actual physical system and a new virtual replica, hosting all the data of the physical artifact. This is referred to as the "twinning" or "mirroring" of an actual physical system throughout its life with a connected virtual system (Quaye, G.M, 2021)

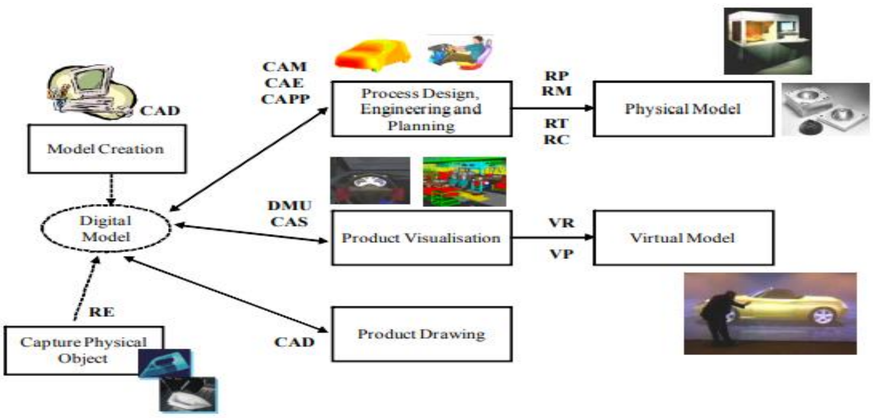


Figure 2. Product Lifecycle Management (Grieves, 2006)

In 2012, NASA formally defined the term "Digital Twin" (DT), recognizing the enormous potential it has for the discipline of aerospace engineering (Bhatti et al., 2021). Since then, extensive study has been conducted to determine how digital twin concepts might be used practically in fields other than aeronautical engineering. Digital conceptions were generally stationary and confined to a few sectors, such as aerospace and manufacturing, between 2013 and 2017. This is explained by the technologies necessary to put them into practice, including information and communication technology, sensor and monitoring technology, the Internet of Things (IoT), and big data simulation and analysis technology, according to Pronost et al. (2021). With the advent of Industry 4.0 and the development of fields like Big Data or the Internet of things, these needs cannot be met (IoT). Large amounts of data may be collected and processed due to technological advancements in this domain, making it feasible to acquire important information. (Pronost et al., 2021). DT was ranked among the most promising technologies for the upcoming decades by Gartner in 2017 and 2019. (Kumar and Teo, 2021).

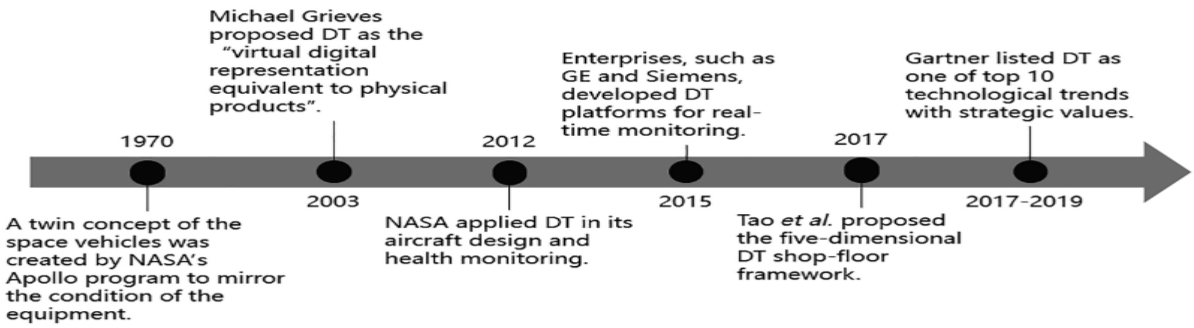


Figure 3. Historical evolution of Digital Twin. (Hu et al., 2021)

2.2 Theoretical Aspect of Digital Twin

A digital twin is a hype term. It is often used in today's discussions about digitalization, smart production, and industry 4.0 (Peng et al., 2020). Based on the literature review of digital twin (DT) terminology and concepts, the definition of digital twins varies depending on the industry/domain and its purpose/usage. All industries have defined the digital twin according to their specific domain perspectives, However, most terminology overlaps with some specific to their industries. Some of the definitions of digital twin from prominent industries players are mentioned below;

Table 1.Definition of DT from various sources (Own Work)

References	Definitions
(Grieves, 2016)	"Digital Twin (DT) [...] 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. [...] That describes [...] Operational States captured from actual sensor data, current, past actual, and future predicted. [...] for a variety of purposes"

(Autodesk, 2021)	"A digital twin is a dynamic, up-to-date replica of a physical asset that brings together design, construction, and operational data. With the addition of real-time operational data, digital twins acquire the behavioral awareness necessary to simulate, predict and inform decisions based on real-world conditions"
Siemens	"A digital twin is a virtual representation of a physical product or process, used to understand and predict the physical counterpart's performance characteristics. Digital twins are used throughout the product lifecycle to simulate, predict, and optimize the product and production system before investing in physical prototypes and assets".
buildingSMART International	"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 twins regularly exchange data throughout the PBOD lifecycle and use phase. Technology like AI, machine learning, sensors, and IoT allows for dynamic data gathering and right-time data exchange to take place".
Wikipedia	"A digital twin is a virtual representation that serves as the real-time digital counterpart of a physical object or process".
SPHERE	"A Digital Twin is a dynamic, virtual representation of a building, its assets, processes, and system".
IBM	"A digital twin is a virtual representation of an object or system that spans its lifecycle, is updated from real-time data, and uses simulation, machine learning, and reasoning to help decision-making".

According to (Hu et al., 2021), the definition of DT illustrated above in different applied fields reveals the following commonalities;

- The foundational element of DT includes a physical object, virtual counterpart, and connection between them implicitly and explicitly.
- Data transmission between the physical artifact and the digital model is highlighted.

2.3 Industrial evolution (Industry 4.0)

Industry 4.0 was conceptualized based on the fourth industrial revolution that has taken place in the manufacturing industry (Ghobakhloo, 2020). Industry 4.0 has contributed to significant digitalization of the manufacturing industry impacting the entire value chain. One of the biggest innovations of industry 4.0 was digital twins concepts and technologies that were widely adopted by many industries (Quaye, G.M, 2021). Industry 4.0 promotes an open, smart manufacturing platform for industrial-networked information applications. Real-time data monitoring, tracking of the status and positions of the product smart control of production processes are some of the outcomes achieved through the application of DT concepts and technologies. (Vaidya et al., 2018).

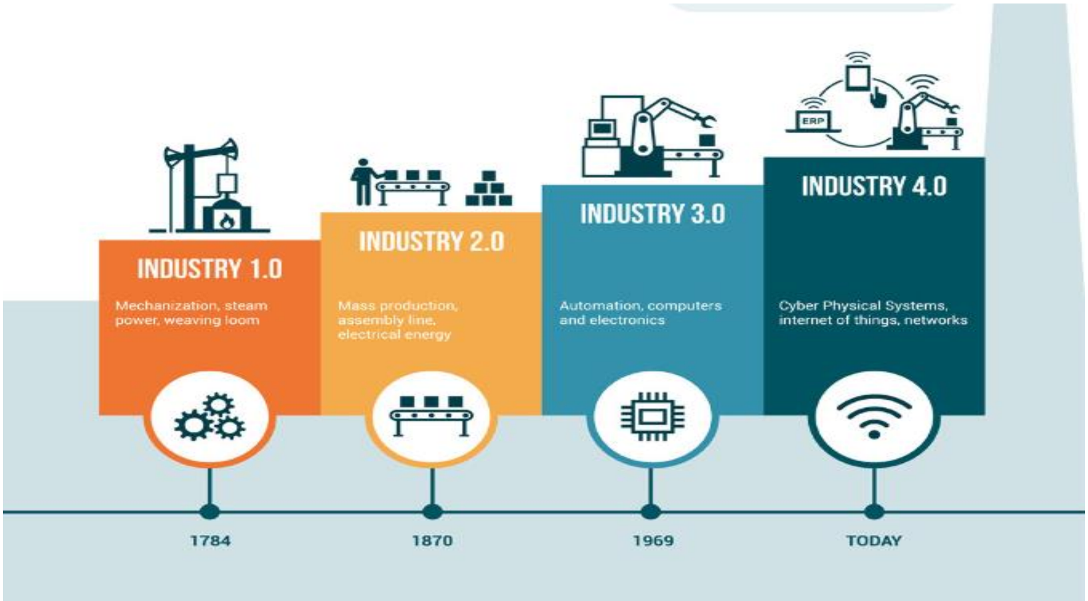


Figure 4. The great industrial revolutions, (Ghobakhloo, 2020)

According to (Maskuriy et al., 2019), The first industrial revolution started with water and steam-powered engine (1784), the second industrial revolution was mass production powered by electric energy (1870), and the third revolution started a program logic circuits (PLC), and information technologies (IT) systems (1969). During the same era, the AEC industry evolved with computer-aided design (CAD), and prefabrications and gradually entered into the 3D design (object-oriented design).

The era of industry 4.0 started in the year 2011 with a higher level of value and control which was not possible in the prior era (Vaidya et al., 2018). In the manufacturing sectors, more innovative processes and control emerged such as smart machines, smart factories, and Cyber-Physical Systems (Quaye, G.M, 2021). Industry 4.0 enables smarter ways of manufacturing production in the factory through integrations of multiple connected systems. The triggering technologies were Digital Twins, IoT,s, sensors, big data, cloud computing, systems integration, AR/VR, and simulation engines (Quaye, G.M, 2021).

Big Data and Analytics; Real-time decision-making will increasingly rely on the gathering and processing of data from heterogeneous sources, including customers, business management systems, and production equipment or systems. The record indicates four components that make up big data: quantity, variety, speed of creation and analysis of new data, and value of the data (Vaidya et al., 2018).

Data analysis of previously collected data is used to identify threats that have previously happened in various production processes in the industry, forecast new concerns, and provide potential solutions to prevent them from happening repeatedly (Maskuriy et al., 2019).

Autonomous Robots; In locations where human workers are not allowed due to several risks, an autonomous robot is employed to carry out autonomous manufacturing procedures with more accuracy. Robots that operate autonomously may execute tasks quickly and accurately while putting a strong emphasis on teamwork, flexibility, and safety. (Vaidya et al., 2018).

Simulation: The physical environment, including processes, machines, products, and people, is replicated in a virtual model using real-time data. This improves decision-making by allowing for insights obtained from various parameter adjustments and visualization. For virtual commissioning, simulation of cycle times, energy usage, or ergonomic features of a production facility, 2D and 3D simulations can be produced saving huge amounts of cost and time. It is possible to reduce product failures during the startup phase and shorten downtimes by using simulations of production processes. Additionally, to increase the robustness of processes, simulations are utilized to reflect what-if scenarios (Quaye, G.M, 2021).

System Integration: Three types of integration primarily characterize Industry 4.0: (a) horizontal integration throughout the entire value chain, (b) vertical integration and networked manufacturing systems, and (c) end-to-end engineering throughout the lifecycle. Automation of vertical and horizontal manufacturing processes includes entirely digital integration, automation, and communication (Quaye, G.M, 2021).

The Internet of Things; Internet of things (IoT) stands for a worldwide network of interconnected and uniform addressed objects that communicate via standard protocols (Vaidya et al., 2018). The main purpose of IoT is to support data sharing and enable seamless communication from the physical environment through sensor networks with the digital counterpart. The emergence of IoT technologies aided many industries to achieve automation in their field. (Kumar, et al., 2019).

Cloud-based platform; Serves as a technical backbone for the connection and communication of elements essential in the DT. Companies generate a tremendous quantity of data during their lifecycle. These data are frequently shared within and outside the organization for multiple reasons. Building the own database and server to host the data shall result in significant cost implications both for infrastructure and maintenance. Therefore, a cloud-based platform is regarded as one of the most essential components necessary for DT operation. Other technologies associated with the fourth industrial revolution are augmented reality (AR) and virtual reality (VR) (Vaidya et al., 2018).

2.4 General Concepts of Digital Twin

2.4.1 DT Model

According to (Boje et al., 2020), the concepts of the DT can be expressed using three main components which include the following,

1) Physical elements

2) Connected data

3) Virtual counterpart

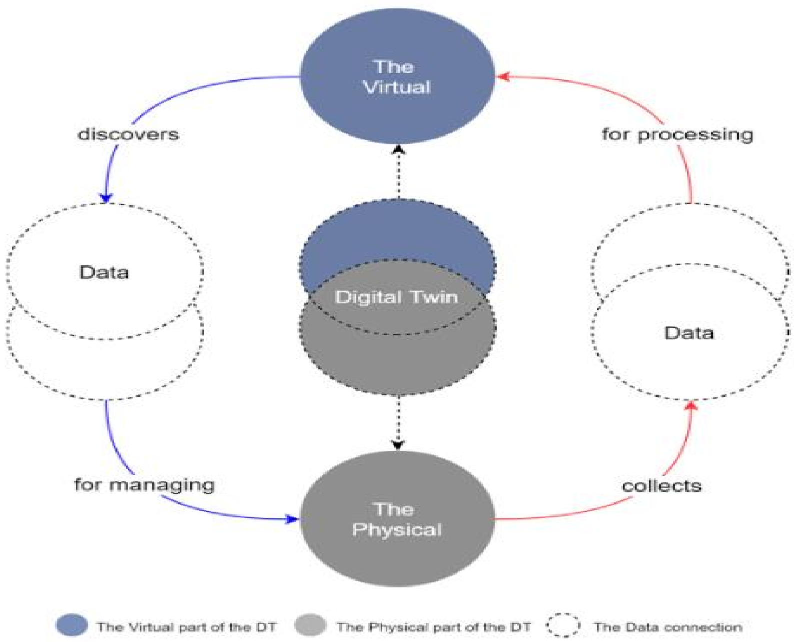


Figure 5. Digital twin paradigm. (Boje et al., 2020)

The features and applications of digital twin models across industries are largely similar in design, delivering dynamic and real-time data for planning and controlling activities. (Boje et al., 2020), The connecting loop between the Virtual to Physical system and the data in various forms is the fundamental component of any digital twin model. The data traveling from the Physical object to the virtual comes in raw format and required some amount of processing, on the contrary, data moving from the digital model to the physical objects are subjected to several transformations. These data are regarded as processed information from data analytics and stored knowledge in digital models. The final output of analyzed data is pushed back to the Physical system through human interventions or automatic mechanical actuators. Essentially, the real-world data fed from physical systems to the virtual models are being processed and analyzed based on embedded engineering models to manage the physical object/asset efficiently.

2.4.2 DT Classifications

According to Wikipedia,("Digital twin," 2022), " A digital twin (DT) concept is classified into the following types;

Digital Twin Prototype (DTP); DTP includes the design, analysis, and processes to create a physical product. DTP existed before the physical product.

Digital Twin Instance (DTI); DTI is a digital copy of a solo version of a product after the product is manufactured.

Digital Twin Aggregate (DTA); A DTA is an aggregation of DTIs whose data and information can be used for querying, predicting, and understanding the physical product. The specific information contained in digital twins is determined by use cases. The digital twin is only a logical construct and does not necessarily contain the data and information in itself. The actual data and information may be stored in other applications connected through semantic meaning and ontology relationships ("Digital twin," 2022).

(Pronost et al., 2021) developed further classifications of DT based on their maturity level (digital model, digital shadow, digital twin) and integration level. The decision tree of the Digital Twins subcategories used is shown below;

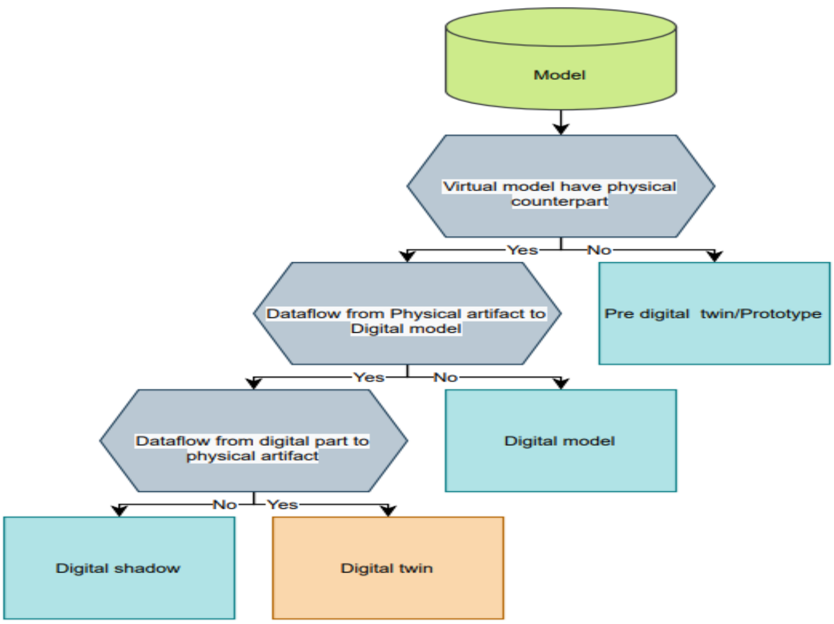


Figure 6. DT classifications framework (Own work)

(1) **Pre-Digital Twin**; This version of DT contains only a digital model; There are no physically existing object counterparts yet. This model can only be created using the theoretical data

provided at the model's input. Before the actual system is implemented, this form of DT is generally created during the design phase to test the design outcomes and reduce potential risks.

(2) **Digital Model**; Any digital depiction of a physical item that "does not use any sort of automated data interchange between the physical object and the digital object" is referred to as a digital model (Fuller et al., 2020). This class of digital twins has a physical counterpart, unlike pre-DT. It is possible to feed a digital object with measured data from the input and output of the real system and compare the reliability of its output response to that of the real system. . The digital model enables comparison between the virtual representation of the object it represents and the actual object to ensure accuracy.

(3) **Digital Shadow;** According to (Fuller et al., 2020), A digital shadow is a virtual representation with a singular automatic data stream, such that when the actual object changes, the digital copy is updated automatically. However, reverse dataflow is limited. Instead of automated feedback loops caused by changes in the digital representation that are based on simulations, changes to the physical system only come about as a result of more conventional human judgments. Its uses include predictive maintenance and real-time operation visualization.

(4) **Digital Twin;** Digital twins are composed of a physical entity and a digital entity which are connected via a network to allow for seamless connectivity and continuous information sharing via direct physical communication or through indirect connections based on the cloud. The automatic input to the virtual object enables the dynamic updating of the model. The goal is then accomplished by using the model to create an effective command for the physical equivalent of the virtual object. DTs can optimize processes carried out by the actual system, such as manufacturing operations optimization.

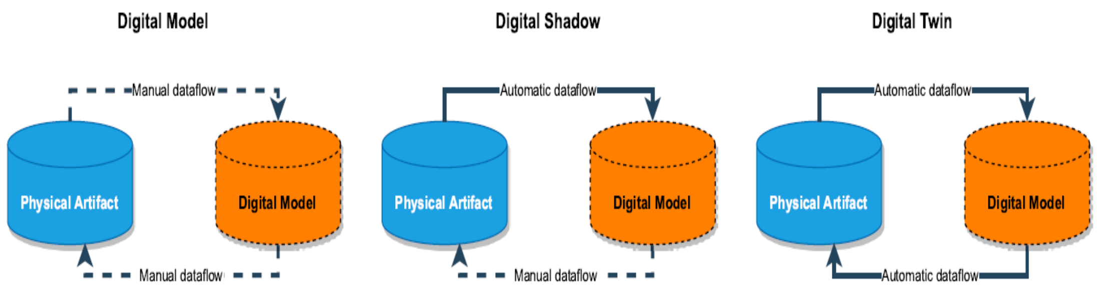


Figure 6. DT Classifications based on Dataflow (Own work)

According to Autodesk, digital twins are created at different levels of assets in a scalable manner beginning from a single component to an asset, process, system, or network of the system for the entire city or country;

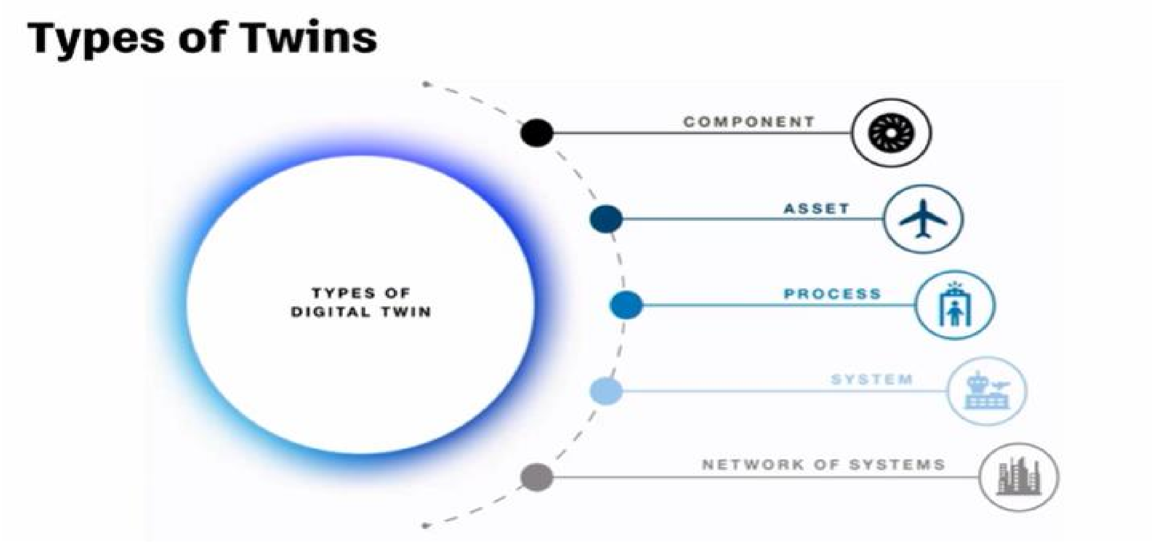


Figure 7. DT types (Autodesk, 2021)

2.4.3 DT Characteristics

As per (Singh et al., 2021), some of the common DT features and characteristics are summarized below;

High-fidelity; This is governed by the standard of the parameters, their correctness, and the extent to which virtual and physical counterparts have been separated from one another. A highly realistic digital model aids DT in accurately reflecting every feature of its actual twin (Singh et al., 2021). When given a variety of potential outcomes or scenarios, highly detailed DT makes simulation and prediction systems more accurate (Jones et al., 2020).

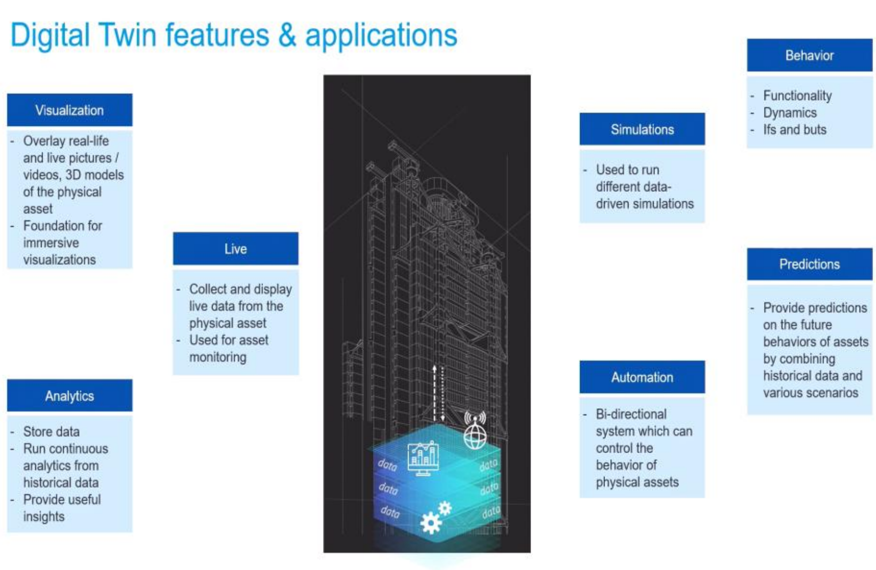


Figure 8. Digital twin features (Deloitte, 2020)

Dynamic; The dynamic aspect is signified by its response relative to time. DT model should be capable of changing the physical system as per a change in physical parameters or inputs fed either manually or automatically (dynamic data, historical static data). This is enabled through the seamless exchange of dynamic data continuously between the physical and virtual models. The dynamic nature of DT is indicated by its ability to realistically mimic the physical twin in the digital world

Self-evolving; DT changes throughout its life cycle along with its physical counterpart. A closed feedback loop results from any change in either the physical or digital counterpart reflecting itself in the other. With the support of the data gathered by the physical object in real-time, DTs are capable of self-adapting and self-optimizing, evolving throughout their existence alongside their physical counterparts (Barricelli et al., 2019).

Multiscale and Multiphysical; The properties of the physical twin must be integrated into DT, which is a virtual clone of its physical twin, on one or more levels. As a result, the virtual model in DT is based on the physical pair's macro-geometric characteristics, such as shape, size, tolerance, etc (Singh et al., 2021). DT is also multiphysical because in addition to the aforementioned geometric characteristics, the model is also based on the physical characteristics of the physical twin, including material characteristics like stiffness, strength, hardness, and fatigue strength as well as structural dynamics models, thermodynamic models, stress analysis models, and fatigue damage models.

Multidisciplinary; The primary aspect of Industry 4.0 is the digital twin Which evolved as the result of multidisciplinary fields such as information technology, computer science, electrical, mechanical, electronic, and communications.

2.4.4 Digital Twin Process

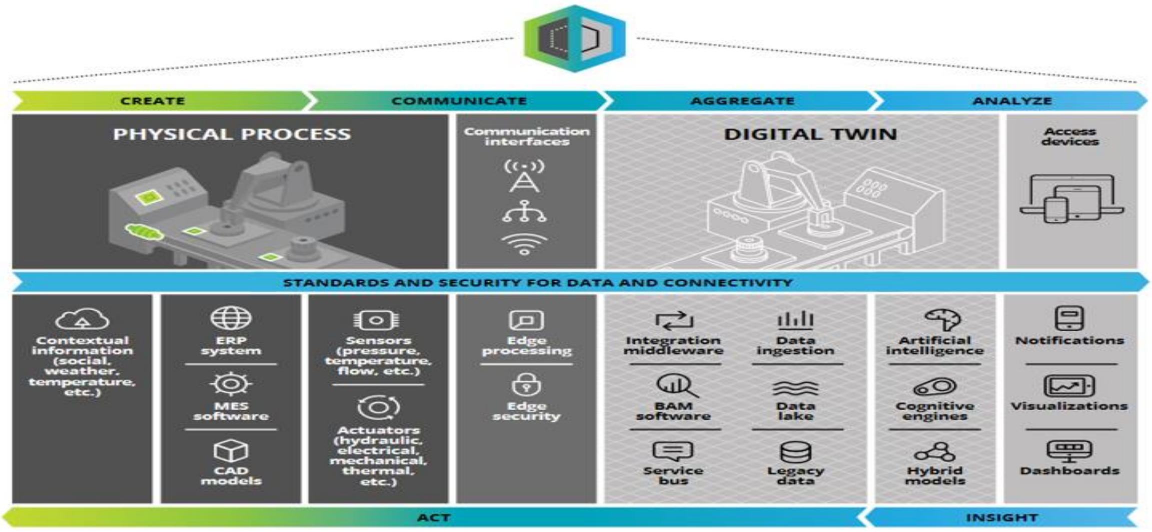


Figure 9. DT conceptual arthitecturearchitecture. (Deloitte, 2020)

Create; To conduct critical measurements of the input from the physical process and its surroundings, the first step is to equip the physical process with a variety of sensors. Two types of sensor measurements are deployed. (1) Performance indicators of the physical standards set for an asset, (2) External data influencing the performance of physical assets. Sensor readings are transferred to the digital twin after being encoded into secure digital signals. Process-based information from systems like manufacturing execution systems, enterprise resource planning systems, CAD models, and supply chain systems can be included to improve sensor signaling. As a result, the digital twin will have a stream of data that is continuously updated for use as input in its analysis.

Communicate; Communication between the physical process and the digital platform facilitates seamless, real-time, bidirectional integration and connectivity. One of the revolutionary innovations that made the digital twin possible is network communication, which consists of three main parts: Edge processing, Interfaces for communication, and Edge Safety

Aggregate; Data is processed and prepared for analysis and can be imported into a data warehouse. Data processing and aggregation are possible both on-premises and on cloud platforms. Recent advancements in the fields of technology that support data collection and processing have made it possible for architects to design designs that scale more quickly and inexpensively than in the past.

Analyze; Data analysis and visualization are done. Advanced analytics platforms and technologies can be used by data scientists and analysts to build iterative models that produce insights and suggestions and help people make decisions.

Insight; Insights from the analysis are provided through dashboards with visualizations, exposing unanticipated differences in the performance of the digital twin and the physical world model at one location. or multi-dimensional, and they might highlight areas that require additional scrutiny and modification.

Act; To fulfill the goal of the digital twin, this stage enables the actionable insights to be collected and transmitted back to the physical asset through the digital process. After passing through the decoder, the data is sent to the asset's process actuators, which are in charge of the movement or control mechanisms, and is subsequently updated in back-end systems that control the supply chain. response control and behavioral management affecting people. The closed loop connection between the physical world and the digital twin is completed by this interaction.

2.4.5 DT Benefits

From Autodesk's perspective, Using digital twins, it is possible to see an asset from many different angles, including how it is used, how it is used, how much space is being used, and how traffic flows through it. A digital twin offers a method to explore "what-if" scenarios, such as the ramifications of design modifications, adverse weather conditions, and security threats. It gathers a significant amount of data in one location. The value from operations is exponentially improved, development effort is reduced, and time to market is accelerated by creating digital twins of complex assets, factories, and processes.

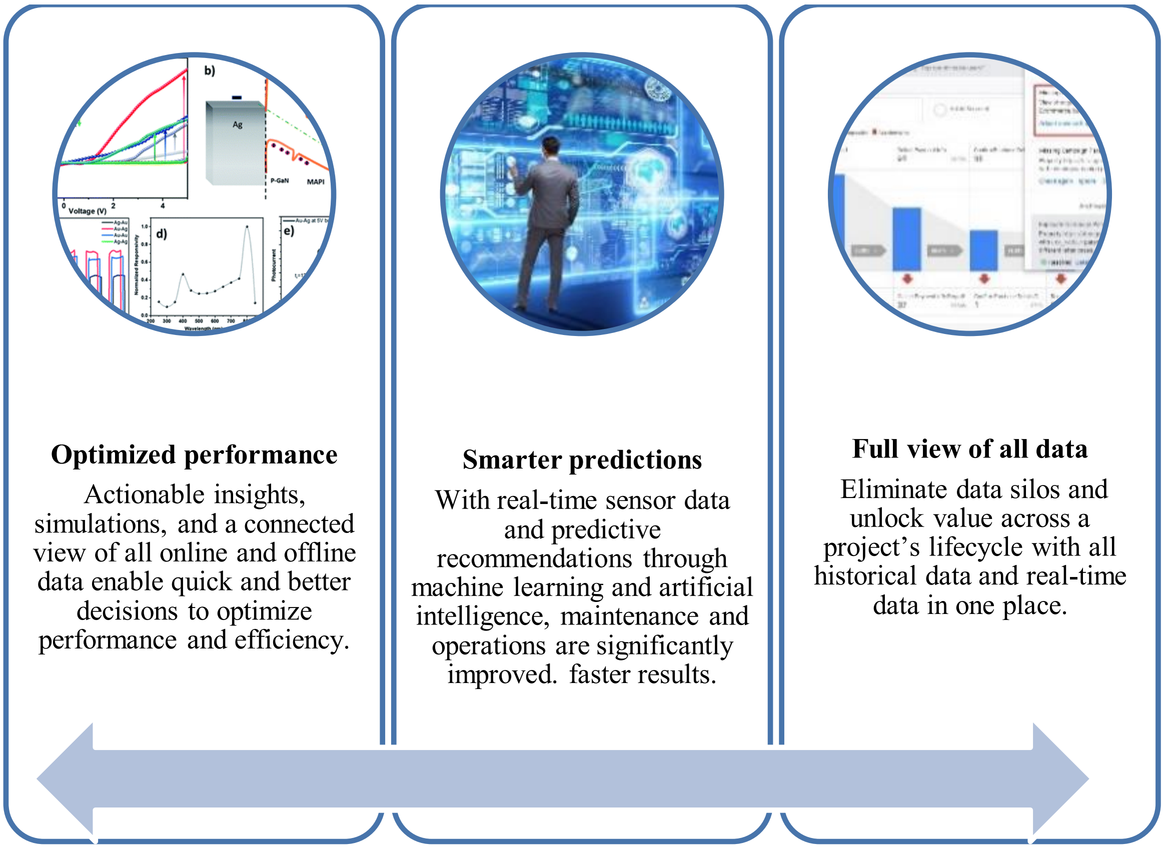


Figure 10. Benefits of DT (Own Works)

2.4.6 DT Foundational Technologies

To support DT creation, a variety of enabling technologies is required to be deployed. (Fuller et al., 2020; Hu et al., 2021; Tao et al., 2019) proposed the following enabling technologies for DT;

Table 2. DT enabling technologies ((Hu et al., 2021)

Application area	Functionalities	Technologies Deployed
Technologies for physical objects	To measure the parameters of the real-world and physical object	Reverse engineering, image recognition, particle detection, and IoT sensing technologies
	Control technologies deployed for controlling a physical object	determining a power source (such as electrical or hydraulic power), designing a mechanical

		transmission (such as a gear, belt, or connecting rod drive), and control technologies (e.g. programmable control, supervisory control, simulation-based control, etc.)
Data construction and management technologies	Enabling technologies for data storage and extraction from physical to virtual system and vice versa	IoT technologies used are QR code, barcode, radio frequency identification (RFID)
	Data storage and linking technologies	MySQL database, Hbase, NoSQL database
	Data mining, Processing, visualization and advance data analytics	Statistical analysis, predictive modeling, data mining, text analysis, optimization, real-time scoring, and machine learning are all examples of data mining. Data visualization uisng tables and graphics (histograms, bar charts, pie charts, etc.). Using extract, transform, and load (ETL), which includes Kalman filtering, image regression, principal component transform (PCT), the K-T transform, the wavelet transform.
Virtual modeling technologies	Technologies to model geometry of virtual counterpart (shape, size, position and assembly relationship), behavioural model, rule based model	computer-aided design (CAD) software such as Revit, Autocadd, solidworks, K-means, and neural network, semantic data analytics, and XML-based specific data

		format (AutomationML, and CityGML
Services technologies	Based on the objectives, types of service technologies varies accordingly. (prediction, monitoring, diagnosing, service life, real-time visualization)	Real-time visualization using computer graphics, 3D rendering technology and image processing.
Connection and data transmission technologies	To realize real-time control and virtual-real state mapping, connection methods with high fidelity	Wireless transmission technologies include Zig-Bee, Bluetooth, Wi-Fi, ultra-wide band (UWB), and nearfield communication. Wire transmission technologies include twisted pair (category 5 and 6), coaxial cable (coarse and fine), and optical fiber (single-mode and multimode) (NFC) GPRS/CDMA, digital ratio, spread spectrum microwave communication, wireless bridge, and satellite communication are examples of long-distance wireless transmission technologies.
Environment coupling technologies	Environmental mapping technologies	technologies for remote sensing, the seismic wave approach, polarization, radio navigation, hydroacoustic location, and 3D modeling
	Visualization of environment	Wearable gadgets with immersive stereoscopic displays (such as head-mounted displays and haptic gloves) integrated with virtual reality (VR) and mixed reality (MR)

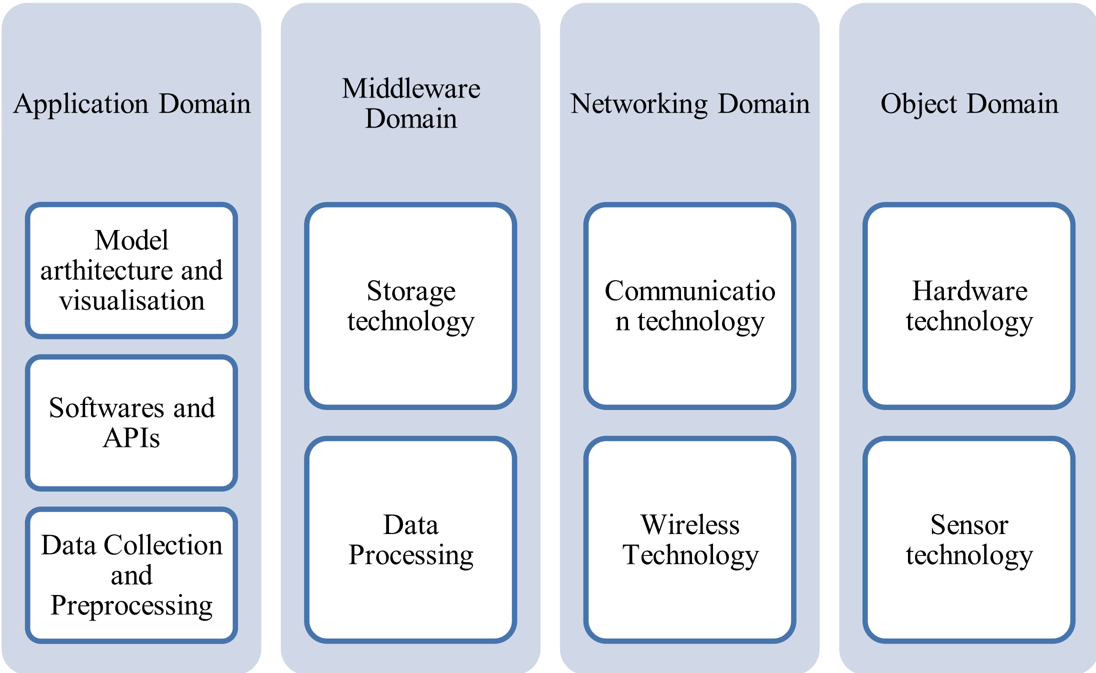


Figure 11. Domain-based DT technologies ((Fuller et al., 2020)

2.4.7 DT Lifecycle Use

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

Design Phase; Digital Twin Prototype (DTP) is utilized to evaluate how hypothetical assets will behave, validate different design choices, ensure that the product meets standards, avoid failure, and maintain product quality (Tao et al., 2018). The development of CAD software has enabled designers to produce complex 3D models that can communicate clearly in a variety of settings, which has made the digital twin feasible. Increasing simulation capability helps to ensure product quality, avert failure, and exceed expectations. The DTP process includes stages for conceptual design, detailed design, and virtual verification and highlights the benefits of testing a design utilizing information on the physical qualities of clients, materials, equipment, and environments, as well as historical data from the most recent generation before manufacture begins.

Build/Manufacture Phase; For the production stage, the concept of the digital twin is used to create Digital Twin Store Floor (DTSF) by merging physical space and information space. (DTSF) supports efficient production planning, resource allocation, and control of the manufacturing process. DT architecture for this phase consists of Physical Shop Floor (PS), Virtual Shop Floor (VS), Shop Floor Service System (SSS), and Shop Floor Digital Twin Data (SDTD). This DT framework allows the owner to predict the outcome of the unit/shop through simulations of different situations enabling the owner to choose the most optimized manufacturing solutions. Costly downtime of the factory can be avoided and predictive maintenance can be made possible. This continuous flow of dependable information enables more rapid, effective, and reliable production processes. (SIEMENS, 2020).

Operational/Service Phase; This lifecycle phase is defined by heterogeneous and extensive layers of data that characterize the use and maintenance of the product and materials. An inefficient operation and maintenance strategy will lead to the risk of costly failure and threats to the operator. DT concepts can support proactive maintenance based on the strategic asset management principle such as using specified material, and correct structural configuration as compared to the conventional approach of the run to failure maintenance. (Tao et al., 2019) devised a framework based on real-time monitoring leveraging cutting-edge hardware and network technologies, enabling data on energy usage, user behavior and configuration, product performance, materials, component wear details, etc. Real-time and historical data integration makes it easier for the service owner to comprehend the status of the operation, including energy consumption analysis and forecasting, user management and behavior analysis, operational guidance for users, intelligent optimization, and updating, product failure analysis and prediction, and product maintenance plan.

2.5 Digital twin in the AEC Industry

It is evident from the preceding sections, the DT paradigm has gained significant traction in the manufacturing and aerospace sector as a means to tackle PLM-related issues and foster greater efficiency and productivity. On the contrary, the AEC industry is not able to fully embrace the DT concepts and technology from the fourth industrial revolution due to industry fragmentation. However, with significant technological advancement within the AEC industry, the concept of a digital twin is being increasingly deployed throughout the lifecycle of Building and infrastructures reshaping the entire industries. This chapter aims to analyze the cutting-edge DT concepts utilized by the AEC industry throughout the different phases of its life cycle. Among the many industry players involved in the implementation of the DT concepts and technologies, some of the most pioneering organizations making significant contributions to the research and implementation of DT in the AEC sectors are BuildingSmart, CDBB (Center for digital built Britain), and 4 years SPHERE project. The summary of their notable contribution is discussed below;

2.5.1 Building Smart Perspectives

The building smart initiatives (bsi) (buildingSMART, 2022) contend that the adoption of DT transformational technologies by the built environment can generate significant value (economic, social, environmental, and business). However, to unlock the benefits of DT, the built industry should break the existing organizational silos among the stakeholders and adopt collaborative practices. The implementation of DT by the built environment will incur huge investments due to the paradigm shift in technologies required. The built asset industry remains constantly challenged by demographic change, urbanization, and climate change in addition to the normal aging and renewals demands of an asset, causing enormous cost and budget implications. These factors demand the built asset industry be more productive and innovative throughout its lifecycle. To counter the pressure exerted on the poor performance of the assets, data-driven solutions are viewed as one of the most potent means to optimize business processes, manage capacity constraints, boost productivity, and ultimately drive organizational performance (buildingSMART, 2022).

The primary mission of building smart initiatives (bsi) is to provide the platform for developing open digital solutions and standards for the adoption of DT in the built asset industry. the organization supports the industry by delivering an open international standard to enable digital ways of working and ensures the successful implementation of the DT concept. Building smart believes that, with better data management and governance and further integration with standardization, the digital twin of any system can be easily created. (bsi) is also responsible for bridging the gap among the key organizational bodies to integrate the technologies and align the schemas with IFC protocols. (bsi) focuses on technical aspects (data exchange standards, protocol specifications), as well as vocabulary definition, business processes definition, and common use case identification (buildingSMART, 2022).

Building smart describes DT as the digital replicas of physical assets across all phases of the PBO-I (Plan-Build-Operate-Integrate) lifecycle. Digital twin aids in better planning and design during the early stage of a project and provides optimization and productivity during the O&M phase. Enabling technologies such as IoT sensors, artificial intelligence, and machine learning facilitate real-time data exchange between the physical and digital counterparts and supports data analytics which enables better decision-making and timely action. With connected assets, the ecosystem of a digital twin for the whole built environment can be created to deliver greater value to the nation (buildingSMART, 2022).

For the AEC player to enable the adoption of digital twin concepts and technologies, (bsi) identifies three critical areas of development which is essential for bridging the existing gaps listed below; (1) data model standards – For collecting and production of data models to operate at various levels, several data models are necessary. This ensures data interoperability between the layers and breaks the data silos. It also enables open, secure, reliable data sharing throughout the industry stakeholders; (2) standards for data management and integration – bind data science and information management together. The standards integrate the data to achieve semantic precision; (3) data security and privacy – (bsi) as the facilitator for creating the enabling environment provides a safe platform for data hosting and sharing (buildingSMART, 2022).

Figure 12.PBO-I lifecycle (buildingSMART, 2022)

2.5.2 CDBB's Perspectives

The Centre for Digital Built Britain (CDBB) is an organization instituted by the UK government to digitize the entire AECOO sector throughout its lifecycle through the adoption of digital twin concepts and technologies. SPHERE is a special purpose vehicle constituted under CDBB to undertake the four years horizon project involving more than twenty partners to jointly develop the digital twin for the design, construction, and operational phase of the building project.

The main objectives of (SPHERE, CDBB, 2020) are;

(1) To create an ecosystem of a digital twin for the entire nation referred to as National Digital Twin. The network of connected DTs ensures better outcomes for the built asset environment. The national digital twin will ultimately support the delivery of better performance, and quality of assets, processes, and systems in the built environment.
(2) To create an information management framework that will enable secure, adaptable data sharing as well as efficient information management.
(3) To create a Task Group for Digital Framework comprising people from academic institutions, researchers, industry players, and government to share knowledge and findings.

One of the important contributions of CDBB is the publishing of Gemini Principles as guidance documents for implementations of the National Digital Twin (NDT) project, Gemini principles provide the best practice of building digital twins through the adoption of nine (9) values (9 main principles).

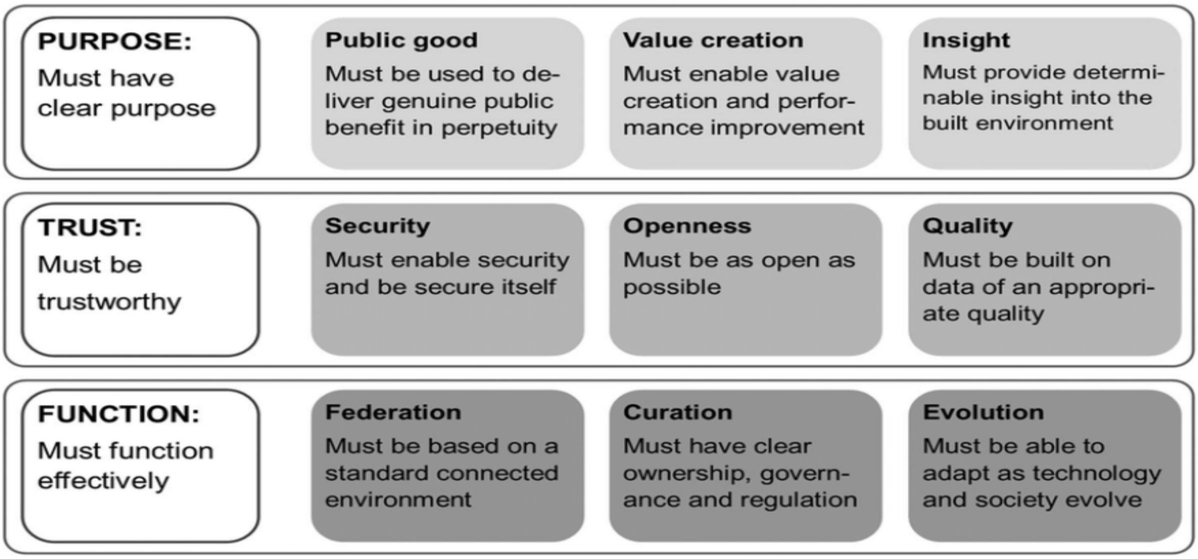


Figure 13. Gemini Principle (Lu et al., 2020a)

The information management framework plays a crucial role in the adoption of digital twins by fostering a common unified language among the stakeholders to exchange and share the asset data efficiently and securely in the machine-readable format. Since the DT requires capturing and exchange of data from multiple sources, the information management framework standardizes the process of data capture and exchange in a consistent manner leading to effective insight and decision-making processes (SPHERE, CDBB, 2020).

To initiate the common definition of DT in the AECOO sectors, CDBB propose new definitions from SPHERE for the building DT as appended below;

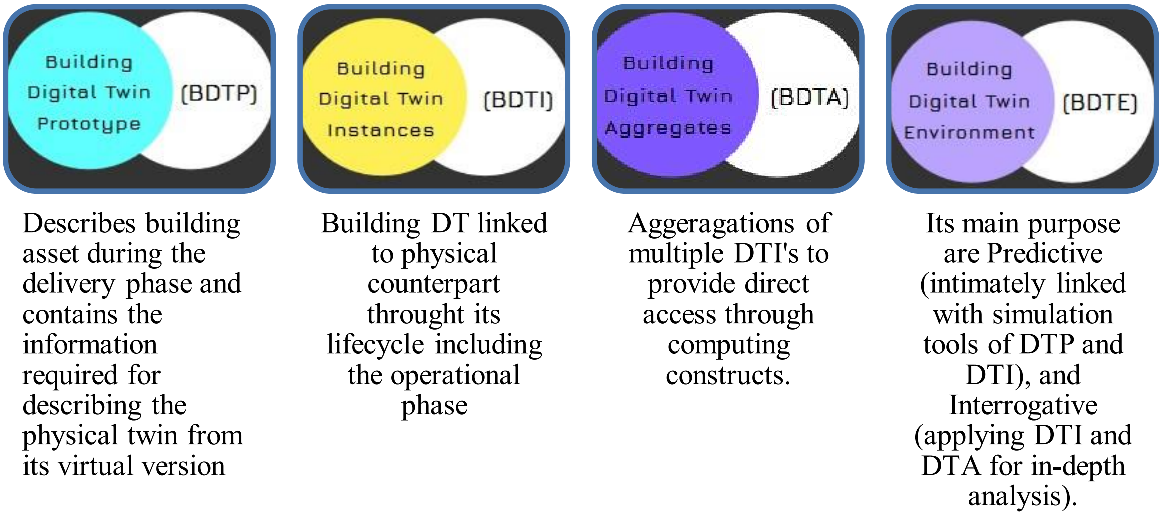


Figure 14.Definition of DT (SPHERE, CDBB, 2020)

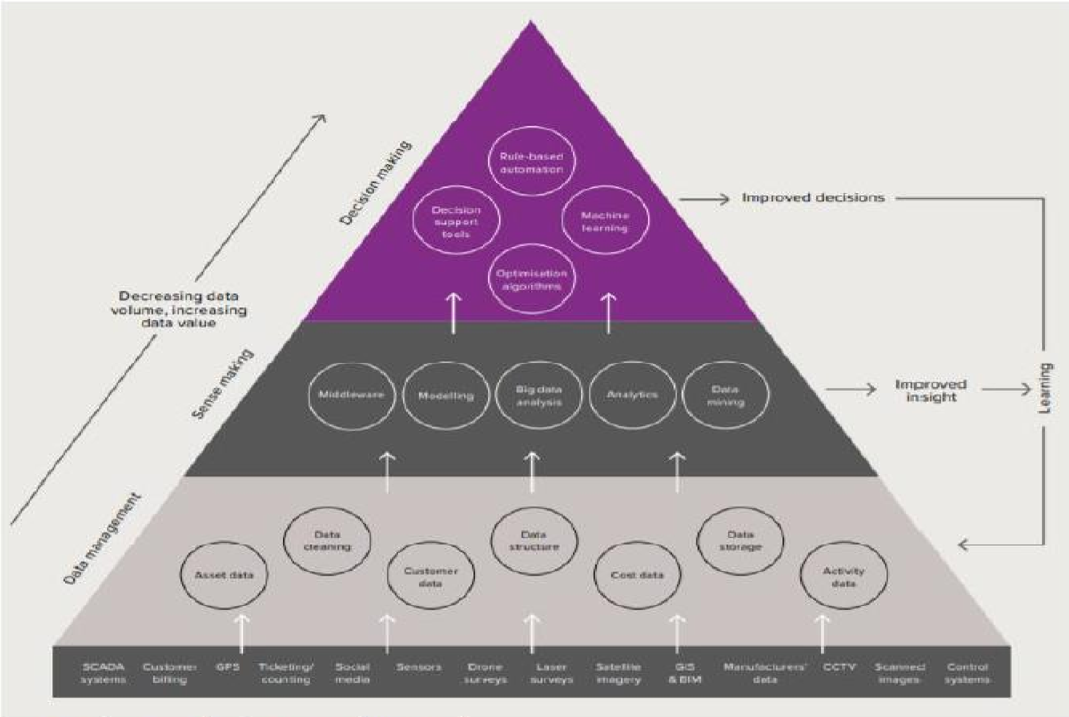


Figure 10 Information value chain Source: (CDBB, 2020)

Figure 15. Information value chain (SPHERE, CDBB, 2020)

2.5.3 Digital Twin Maturity

Maturity element (logarithmic scale of complexity and connectedness)	Defining principle	Outline usage
0	– Reality capture *(e.g. point cloud, drones, photogrammetry, or drawings/sketches)*	– Brownfield (existing) as-built survey
1	– 2D map/system or 3D model *(e.g. object-based, with no metadata or BIM)*	– Design/asset optimisation and coordination
2	– Connect model to persistent (static) data, metadata and BIM Stage 2 *(e.g. documents, drawings, asset management systems)*	– 4D/5D simulation – Design/asset management – BIM Stage 2
3	– Enrich with real-time data *(e.g. from IoT, sensors)*	– Operational efficiency
4	– Two-way data integration and interaction	– Remote and immersive operations – Control the physical from the digital
5	– Autonomous operations and maintenance	– Complete self-governance with total oversight and transparency

Figure 16. DT maturity (Atkins, 2017)

The value & sophistication of DT increases with the level of its maturity. proposed a DT maturity spectrum as shown in Figure 16. Fundamentally, the level of DT maturity implemented should be justified by the corresponding value generation. There are six levels of maturity. The execution of maturity-level is not limited to linear development, sometimes twins at lower maturity levels may exhibit the characteristics of the higher DT, The maturity ranges from element 0 to element 5.

According to Vertantix, the level of digital twin's sophistication is illustrated in figure 17.

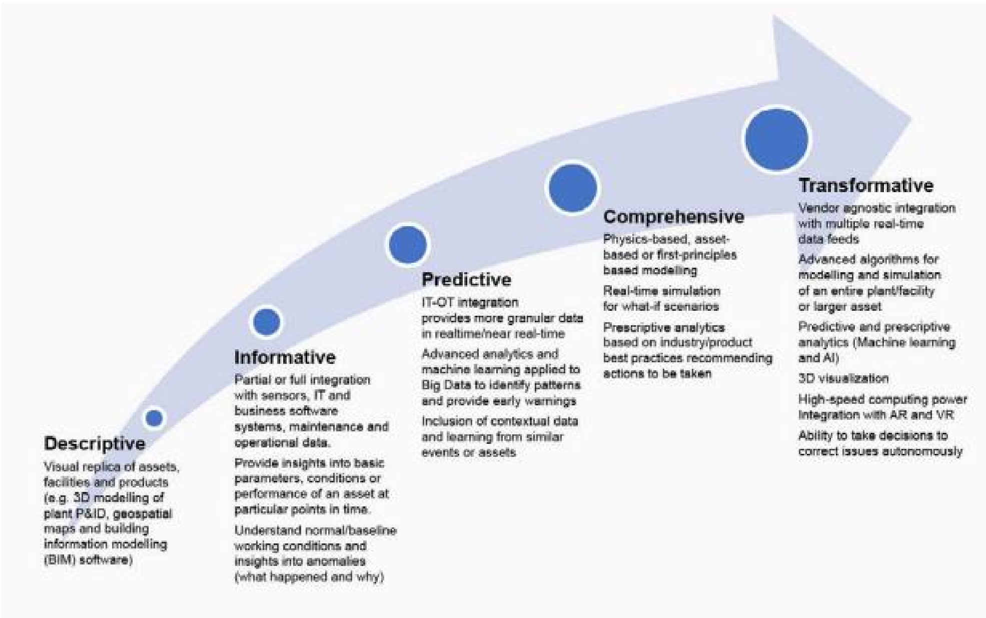


Figure 17. Level of DT sophistications (Autodesk, 2021)

The level of sophistication/maturity of DT is dependent on the volume and caliber of data gathered from the physical twin and its surroundings, according to Singh et al. (2021).

Partial DT: A small number of data points, including pressure, temperature, and humidity, are used to assess the connectivity and functionality of DT.

Clone DT: It contains all crucial details about the system or product that may be utilized to make prototypes and categorize various development stages.

Augmented DT: It utilizes both historical data and data from the asset, and while doing so, it also makes use of algorithms and analytics to synthesize and correlate the relevant data.

The acquisition of more data sets throughout the operation can increase DT complexity. (Azad M. Madni et al.) categorized DT into four levels as follows;

Pre-Digital Twin: DT is created before the creation of the real product to make decisions concerning the designs of prototypes, reduce technical risk, and identify potential problems.

Digital Twin: This level incorporates information about the performance, maintenance, and condition of physical assets. This information is used by the virtual system model to support high-level decision-making in asset design and development as well as maintenance planning. At this level, data transmission is two-way.

Adaptive Digital Twin: Level three uses supervised machine learning to take into consideration the priorities and preferences of human operators and provides a configurable user interface for dealing with the physical and digital twins. With the aid of this DT, real-time planning and decision-making during operations is possible.

Intelligent Digital Twin: Level four adds unsupervised machine learning capabilities in addition to the features from level three. A system's analysis can be carried out more precisely and successfully by integrating it with reinforcement learning, which may help uncover patterns in the operational environment.

2.5.4 Comparison of BIM and Digital Twin

Data generated during the planning and design phases are incorporated into the BIM process. The asset's development and operation are also covered by the digital twin, which can potentially help with future project planning and design. Multidisciplinary models in the core, together with the integration of systems and data across processes and between organizations, are necessary to fully realize the potential of the digital twin. The quickest way to create a precise, valuable digital twin is through BIM.

BIM platforms were developed in response to the need for effective IT tools for design, and the processes have evolved to fulfill the need for digital prototyping in construction, allowing testing of both design and production aspects before construction (Feng, Haibo et al., 2021; Sacks et al., 2020). Many practitioners see BIM as the core technology enabling the construction of digital twins (Sacks et al., 2020), Though so-called "as-built" BIM or "Facility Management" (FM-BIM) models (Teicholz, 2013) include details about the status of facilities when they are put into service, they fall short of the digital twin concept of continuously updating the representation of a facility's current state. The goal of "as-built" models, also known as the "asset information model (AIM)" in ISO 19650, is to give owners models for the operation and maintenance phase. These models are typically reactively compiled after execution. They are not intended to provide the short cycle time feedback needed for project control (Sacks et al., 2020). To show the actual reflection of the physical assets at any given time as in line with the digital twin modeling concepts, the BIMs need to be continuously updated using the information collected from the sensors or ubiquitous IoT devices. However, there has been a lack of efforts to connect BIMs to digital twin models (Feng, Haibo et al., 2021).

Furthermore, the BIM-compatible predictive simulation and analysis tools are intended for use in design rather than project execution. Predictions of the future performance of the built product are made using applications for structural engineering, ventilation and thermal performance, lighting, and acoustics. When performing "4D CAD" analysis of project schedules using BIM models, critical path approach tools are employed, although these are not appropriate for production control (Sacks et al., 2020). Although BIM systems offer excellent representations of product designs, they lack the necessary elements for construction utilizing digital twins. (Sacks et al., 2020)

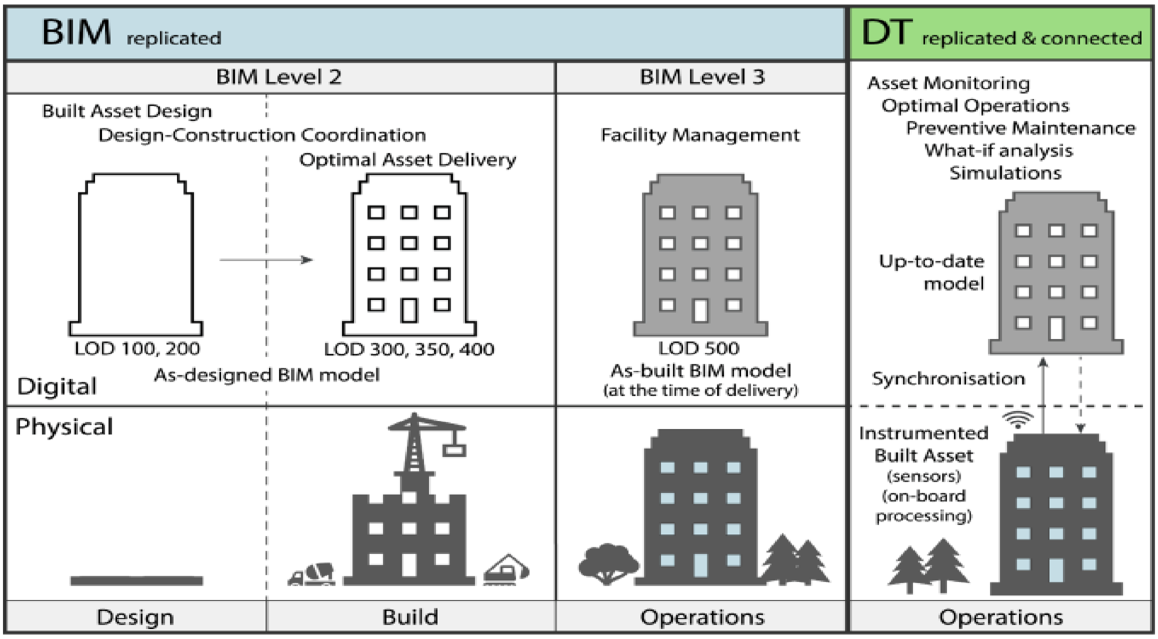


Figure 18. Comparasion of BIM & DT (Davila Delgado and Oyedele, 2021)

However, according to (Quaye, G.M, 2021), BIM is one of the foundational processes on which digitization in the AEC sector is made possible and scalable, The digital twin is regarded as a concept rather than a technology and it relies on many enabling technologies to generate a value. A BIM model is a 3D model with abundant semantic data that acts as a database for all assets and streamlines and standardizes information flows between stakeholders during the delivery phase. BIM model and Cobie data act as a repository of asset data during the operation and maintenance phase (Lu, et al., 2020). However, BIM application in the O&M phase is still at an early stage and requires significant development for integrations. Currently, the Cobie data format is the only means to integrate BIM in the O&M phase. According to research findings, there are many limitations associated with the lack of BIM application and integration in the O&M phase, some of the notable issues are summarised under organizational - the lack of awareness of BIM use in the O&M phase; technological – lack of monitoring integration of BIM-IoT's; the informational-the legacy format of BIM not supporting the integration of BIM with IoT's technologies. However, with the adoption of BIM level 3 in the future, most of the integration issues faced can be eliminated.

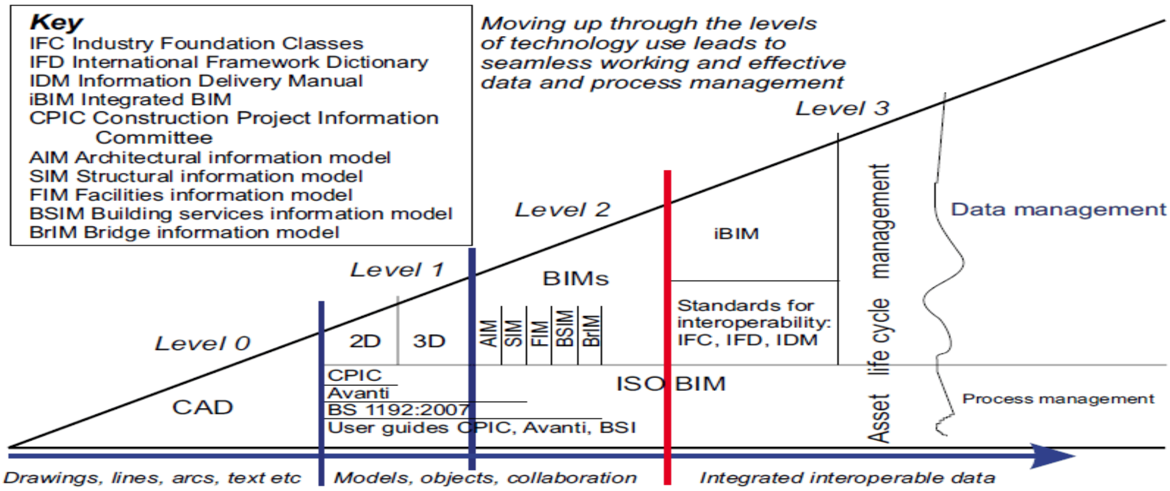


Figure 19. BIM maturity wedge (Quaye, G.M, 2021)

Recognizing the limitation of BIM in the integration of the O&M process, CDBB proposes DT concepts to overcome the integration issue with BIM models. DT supports the integration and interfacing of BIM data with the services delivery processes, in a secure information landscape. DT provides flexibility in information integrations and modeling with analytical capabilities which are not possible with the BIM process. Further, DT adoption can also enable prescriptive and predictive maintenance during the O&M phase. The broad relationship between BIM and DT is illustrated below by (Bart Brink, 2020)

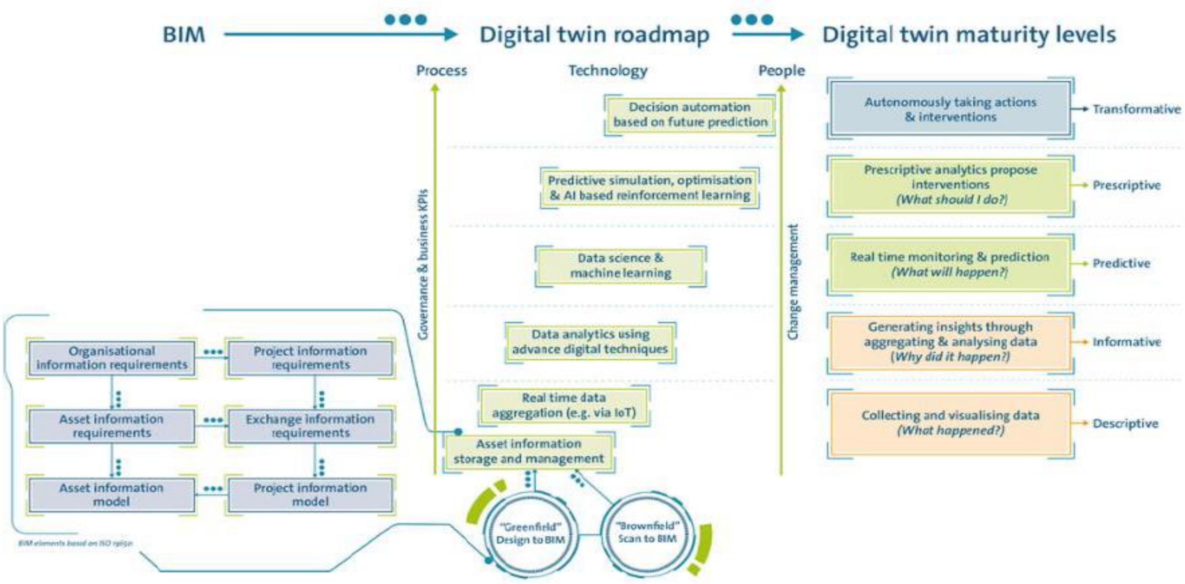


Figure 20. Relationship b/w BIM & digital twin (Quaye, G.M, 2021)

3 LITERATURE REVIEW – STATE OF ART

The definitions of digital twin are specific to the industry domain, Fundamentally, "A digital twin can be defined, as an evolving digital profile of the historical and current behavior of a physical object or process that helps optimize business performance" (Deloitte, 2020). The application of intelligent operation and maintenance strategies, that utilize enabling technologies such as BIM, IoT, ML, and AI capabilities, offers huge benefits to the AEC industry. Many research findings have illustrated the application & benefits gained from the implementation of DT process during the O&M phases, However, many challenges are encountered while implementing the digital twin concepts during the O&M phase. According to a study conducted by Delloite, the most critical knowledge required for implementing a digital twin process is determining the appropriate level of detail in a DT model. Both complex and simple DT models will not yield their true value and incur significant costs to the asset owner. This chapter performs the literature analysis on the state of the art of the Digital Twin concept and identifies practical applications in the real world, particularly during the O&M phase. The following research questions are formulated to find the appropriate solution to create the right level of DT for the O&M phase.

Figure 21. Key questions of the literature review (Own works)

After identifying the relevant papers and articles from various sources available online, the systematic process of literature review entails a review of the application of DT in the O&M phase, a review DT model, and the solution used, information requirements, technology selected, and the frameworks proposed for the practical application. The review was performed following the PRISMA framework utilizing the University of Ljubljana digital library database and Google scholar database. The keywords are combined with Asterix OR X OR, AND, digital twin enabled Asset management/Facility management, Digital twin in operation and maintenance, Digital twins in AEC sectors, BIM enabled digital twin, Smart Asset management Building Operation and Digital Twins. The total resources identified in the Zotero database were 67 including a research paper, conference paper, books, and reports. With further screening, 10 final papers were considered for in-depth qualitative analysis.

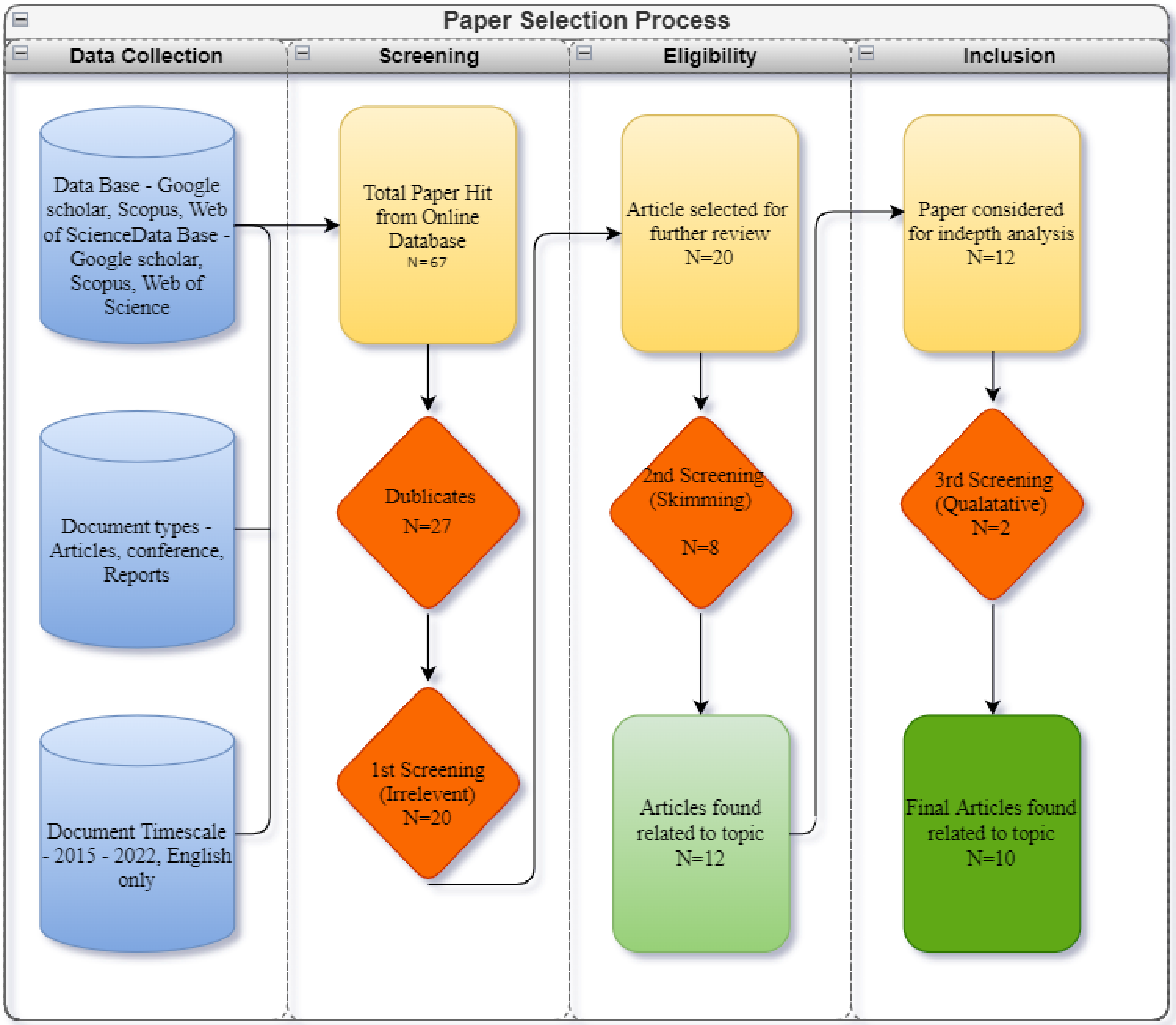


Figure 22.Paper selection process (Own works)

3.1 Literature Analysis

Following the rigorous process of screening the relevant papers, and reading through the selected articles, the papers are summarised based on the thematic area of applications, DT model adopted, tools & technologies used, and value generated from its applications. The findings from this literature analysis is is used as a knowledge base for answering the research question formulated.

Table 3.Ten papers were identified based on the thematic area of applications

Authors	Digital twin Descriptions	Applications phase
(Peng et al., 2020)	"Digital Twin Hospital Buildings: An Exemplary Case Study through Continuous Lifecycle Integration"	O&M
(Zhao et al., 2022)	"Developing the conceptual framework for the application of digital twin technologies to revamp building O&M process"	O&M
(Lu, Parlikad, et al., 2020)	"Developing a Digital twin at Building and city level - A case study of West Cambridge Campus".	O&M
(Lu et al., 2021)	"Moving from building information models to digital twins for the O&M phase".	O&M
(Lu, Xie, et al., 2020)	"Digital twin-enabled anomaly detection for built asset monitoring in operation and maintenance"	O&M
(Coupry et al., 2021)	"BIM-Based Digital Twin and XR Devices to Improve Maintenance Procedures in Smart Buildings"	Smart Asset Management
(Papic and Cerovsek, 2019)	"Digital twins advancing smart infrastructure asset management"	Smart Asset Management
(Lu et al., 2020a)	"From BIM Towards Digital Twin: Strategy and Future Development for Smart Asset Management"	Smart Asset Management
(Heaton and Parlikad, 2020)	"Asset information model to support the adoption of digital twin"	Smart Asset Management
(Qiuchen Lu et al., 2019)	"Developing a dynamic digital twin at a building level: using Cambridge campus as a case study"	DT Modelling – Building Level

Table 4. Enabling technologies adopted for DT in O&M

Authors	Digital twin Descriptions	Enabling technologies
(Peng et al., 2020)	"Digital Twin Hospital Buildings: An Exemplary Case Study through Continuous Lifecycle Integration"	Big Data Analytics, Cloud Storage, Continuous Life Cycle Integration, ETL, Mixed Reality, 3D Point Cloud, and 3D BIM
(Zhao et al., 2022)	"Developing the conceptual framework for the application of digital twin technologies to revamp building operation and maintenance process"	PLC, Wireless LAN, NX Modelling, Line Designer, PLM, O-IM Web server, O-DF
(Lu, Parlikad, et al., 2020)	"Developing a Digital twin at Building and city level - Case study of West Cambridge Campus"	RFID, QR code, Wifi, WP-WAN, CIM, AI, ML, IoT
(Lu et al., 2021)	"Moving from building information models to digital twins for operation and maintenance"	As-is BIM model, WSN enabled IoT, RFID, Cloud Computing, ETL, Autodesk Forge API, AWS DynamoDB, web-based program (.Net) using C# and JavaScript
(Lu, Xie, et al., 2020)	"Digital twin-enabled anomaly detection for built asset monitoring in operation and maintenance"	AMS, BMS, GUID, BAS, Cobie, IFC,
(Coupry et al., 2021)	"BIM-Based Digital Twin and XR Devices to Improve Maintenance Procedures in Smart Buildings"	GPS, XR devices, CDE, HMD,AR, VR
(Papic and Cerovsek, 2019)	"Digital twins advancing smart infrastructure asset management"	CMM, ISO 55000, Digital Built Environment Maturity Model (dbEMM)
(Lu et al., 2020a)	"From BIM Towards Digital Twin: Strategy and Future Development for Smart Asset Management"	3D BIM (extended IFC format), WSN enabled IoT, BMS, AMS, SMS, Cloud computing (AWS), ETL

(Heaton and Parlikad, 2020)	"Asset information model to support the adoption of digital twin"	A relational database, AIM categorization systems ETL, point cloud to BIM, and 3D BIM (REVIT-IFC)
(Qiuchen Lu et al., 2019)	"Developing a dynamic digital twin at a building level: using Cambridge campus as a case study"	RFID, QR codes, image-based techniques, 5G, LP-WAN, BIM, AI, machine learning modules, IoT.

Table 6. Value/Benefits of DT Implementation

Authors	Value Generations
(Peng et al., 2020)	The capacity to get prompt facility diagnoses and operation recommendations that are automatically delivered back from the digital building to reality has been developed, as can understand the precise status of the entire hospital by visual management.
(Zhao et al., 2022)	Create a conceptual framework to aid in the broader use of DT technologies and assist FM during the building's O&M phase.
(Lu, Parlikad, et al., 2020)	The proposed DT architecture facilitates the integration of diverse data sources, facilitates efficient data querying and analysis, facilitates decision-making in O&M management, and further reduces the distance between people and buildings/cities.
(Lu et al., 2021)	It encourages the wider use of DT-enabled asset management during the operation and maintenance phase. It also stimulates new research ideas.
(Lu, Xie, et al., 2020)	The results show and prove that the novel DT-based anomaly detection process flow realizes a continuous anomaly detection of pumps, which contributes to effective and automated asset monitoring in operations and maintenance (O&M) using the centrifugal pumps in the heating, ventilation, and air-cooling (HVAC) system as a case study.
(Coupry et al., 2021)	Demonstrate how a DT may be created using a BIM and how using a DT in conjunction with XR technology can enhance maintenance procedures in a smart building.
(Papic and Cerovsek, 2019)	These paper targets methods, processes, and technologies that may be used to better capture, organize, analyze and understand the status and behavior of infrastructure assets. The presented smart asset management maturity model will enable asset owners to introduce new methods of monitoring and

	decision-making that may lead to innovative smart infrastructure asset management.
(Lu et al., 2020a)	It encourages the widespread use of smart DT-enabled asset management during the O&M phase and contributes to the generation of new research ideas.
(Heaton and Parlikad, 2020)	exemplifies how many models can be federated into a single, larger-scale model to allow a single point of access to data from various models of different assets.
(Qiuchen Lu et al., 2019)	Developing a dynamic digital twin at a building level: using Cambridge campus as a case study

3.2 Review of DT Application and Solution used - O&M phase

Review Article 1 - Digital Twin Hospital Buildings: An Exemplary Case Study through Continuous Lifecycle Integration - (Peng et al., 2020)

Hospital overview screen; A large display screen showing the overview of the hospital operation and maintenance system is set up in the control room which provides the overall visualization of the critical information required for daily checking by the facility manager.

Space management; The spatial information of rooms and corridors was created for effective hospital space planning, supporting room allocation, statistical analysis, and other tasks in the 3D view and list view. This gives each medical department's use rate as well as the proper positioning for the maintenance staff, and the effectiveness of space use was evaluated in light of how the hospital operates (Peng et al., 2020).

Energy management; For monitoring energy consumption such as water and electricity, consumptions are segregated to based on usage for different purposes and locations Both the total energy consumption and individual consumptions (by category) are displayed in the graphic platform with color-coding (Peng et al., 2020).

Facility management; There were displays representing each system's physical structure, logical organization, and key facility information. The operating status and alarm status of each device are shown in the 3D model view during rough seamless docking with BA. The technology allows the backstage management staff to easily understand the operation of all important machinery and assess their performance by displaying the historical monitoring data of each monitoring point as a list and trend chart (Peng et al., 2020).

Repair and maintenance subsystem; This serves as the DT system's service windows, enabling users of any level to easily initiate and handle repair requests or maintenance schedules. This subsystem's DT service consists of work order generation, processing, job assignment, emergency repair initiating, and maintenance calendar. Through fault diagnosis modules, maintenance actions can be carried out according to the real circumstance triggered by a human or automatic system. The DT module helps with accurate fault location, which boosts the effectiveness of equipment maintenance and emergency repairs (Peng et al., 2020).

Security subsystem; By connecting with the hospital's video monitoring platform, the platform was able to combine all security cameras. The DT control center would immediately alert security guards on relevant floors as soon as medical dispute staff entered the field of any security cameras using the security subsystem, which would also trigger facial recognition warnings based on their photo profiles (Peng et al., 2020).

Guest flow management; a real-time guest flow can be tracked based on a facial recognization camera mounted on each entrance. The system calculates the guest flow rate at the set time using ETL processing. As soon as it exceeds the threshold limit set, the warning is initiated informing the security personnel on duty. Vehicle flow can also be traced based on numberplates to determine car flow rates (Peng et al., 2020).

Abnormal electric usage detection; The k-means cluster method was used to automatically classify the data from smart meters, which showed that the amount of electricity consumed in hospitals varies depending on location. To check the unidentified consumption pattern, this process is entirely automated and unsupervised. Data based on at least seven different types of typical consumption are collected, and corresponding smart meters are recognized. The DT system continuously monitored the power usage and identified any anomalous meters that exceeded or fell below the 20% threshold from corresponding normal behavior. On a huge screen, abnormal circuits were displayed, and a mobile app invited users to perform check activities for the rapid maintenance of damaged lines and circuits (Peng et al., 2020).

Air-handling unit fault prediction; Faults are located using information from repair records and the monitoring system, which uses data collected over 24 hours. Long-Term and Short-Term Memory (LSTM) networks were used to learn prediction rules from time-series data because they have a flexible memory and can follow anomalous data changes over time. the LSTM prediction model encompassed 10 different types of failures, including overheating and undercooling, low airflow, blocked filters, and others. The data warehouse, on the other hand, is constantly updated with the most recent 24-hour monitoring data for all AHUs. An early warning would be given in the system and mobile app if the anticipated failure probability was more than 0.6 (Peng et al., 2020).

Frequent repair pattern recognition; The method allows for the automated analysis of all repair and maintenance records to identify the pattern of performed fixes and identify the underlying causes of recurrent failure. The system automatically groups comparable repairs into repair patterns, which were appended to the monthly report. The extracted information included repair floor, department, room, and type of damage. Optimization decisions would be made by managers when they discovered significant trends (Peng et al., 2020).

Low-quality maintenance checking; The DT system makes it possible to keep track of each piece of equipment's maintenance history as well as the identities of the contractors who perform that maintenance by utilizing the t-test hypothesis testing technique. If the mean value of the repair amount sequence following maintenance was higher than it was before maintenance and statistically significant, the quality was deemed low (Peng et al., 2020).

Review Article 2 - Digital twin-enabled anomaly detection for built asset monitoring in operation and maintenance - (Xie et al., 2020)

A case study at the University of Cambridge's West Cambridge campus to demonstrate how the designed data structure can support the data integration of dynamic DT buildings and anomaly detection function. The study showed that the DT platform gives facility managers and other associated stakeholders access to asset monitoring services by analyzing existing anomaly detection modules, and professional expertise and by establishing interaction between the real and digital worlds. The DT system's primary objective is to provide FM personnel with intuitive information, visualization, and decision support, by using the IFC schema and intelligently analyzing these data in a systematic manner. The embedded DT instance implements the intelligent extraction of pump-relevant data and sets off the alarm when the anomaly detection technique detects any potential aberrant behavior for the investigated pump. With the capacity to store and analyze BIM object-related data gathered via heterogeneous data sources, the embedded DT instance may store and analyze data related to BIM objects (Xie et al., 2020).

During the O&M phase, it is discovered that an anomaly detection system is required to identify abnormal pump behavior before it causes any catastrophic consequences as a result of its failure. Since it takes a lot of experience to manually identify anomalies, DT platforms fully equipped with machine learning and artificial intelligence ought to be able to distinguish between various patterns obscured in operational data (Xie et al., 2020).

Review Article 3 - Developing a Digital Twin at Building and City Levels: Case Study of West Cambridge Campus- (Lu, et al., 2020)

The author proposes a dynamic digital replica of a city level with DT sub-systems (building, bridges, transportation, etc). This DT architecture links diverse assets and data sources with their applications, facilitating intelligent asset management, delivering efficient O&M management, and further bridging the gap between human relationships with buildings and cities through more intelligent, transparent, and sustainable means (Lu et al., 2020).

The idea of a DT-enabled smart city was proposed in recognition of the important role that citizens play in urban and city development. This smart city will involve residents and acquire vital feedback on important urban planning and policy through the internet network. (White, et al., 2021)

Review Article 4 - BIM-Based Digital Twin and XR devices to improve maintenance Procedures in Smart Buildings- (Coupry et al., 2021)

BIM-enabled asset management lacks predictive capabilities, Therefore, BIM-based DT uses "Extended Reality".(XR) devices can improve maintenance operations in a smart building. The applications of BIM-DT -XR for maintenance improvement are explained below;

XR device helps to locate or identify specific equipment at the site during maintenance procedures based on data of equipment from a centralized DT or a BIM to identify its location. Devices such as Hololens headsets combined with detection algorithms to facilitate the localization and identification of malfunctioning elements even if the maintenance equipment is hidden or concealed. It can also be used to display specific documentation, such as a 3D representation of an ultrasound inspection. Further through the use of documentation or maintenance instructions, such as equipment documentation or maintenance instructions. Through the use of specific filters, only needed information can be displayed preventing the overflow of too much information to the operator. The use of AR or MR argumentation helps to display specific information over or near the equipment and can help the operator to better identify faulty equipment (Coupry et al., 2021).

Centralization of data made possible by DT enables all stakeholders to access the operation data and analyze the data which can be eventually used for predictive inspection purposes. Sometimes if the operator requires assistance (information related) during certain maintenance tasks due to complex procedures involved, Collaboration then becomes synchronous as it is carried out in parallel with maintenance operations. With the use of video calls and augmented virtual annotations, communication between operator and remote expert can also be established creating a real-time augmentation. After the maintenance procedures, inspection and maintenance reports can also be shared among the stakeholders (Coupry et al., 2021).

3.3 Review of Enabling Technologies Deployed For O&M phase

This chapter examines some of the top important technologies that were deployed in the creation of the DT from among the selected research papers. This review also contributes to the knowledge base for DT creation in the O&M phase.

3.3.1 BIM (Building Information Modelling)

BIM process not only enables digital representation of the building and civil infrastructure but also allows the exchange of Building information effectively among the stakeholders following the unified digital norms. BIM has considered a central repository or database for information exchanged during the design and construction phase of the building and infrastructures (Lu et al., 2021). However, BIM usage in the operational phase has been found limited due to its inability to integrate the dynamic and real-time data from the heterogeneous source. Currently, BIM level 2 use in asset management operation and maintenance phase is at the infancy stage. The existing level of BIM supports the exchange of asset information using the Construction Operations Building Information Exchange (Cobie) spreadsheet. The future evolution of BIM into level 3 has the potential to integrate asset information more dynamically. However, BIM at the current level still serves as the lowest common denominator for building DT due to its ability to host static asset data, accurate representation, communication, and monitoring, and easy retrieval of information about buildings and infrastructure. Apart from exchanges of asset data using the Cobie format for the operational and maintenance phase, BIM also provides the 3D model for visualization of an asset in real-time when integrated with DT architecture. According to (Quaye, G.M, 2021), BIM limitations in the DT process manifest in technology-related challenges, information-related challenges, organizational challenges, and standard-related challenges.

One of the effective methods to create a digital twin in the operation and maintenance phase is demonstrated by (Lu et al., 2020b) using the IFC schema from the BIM model. Industry foundation class (IFC) supports interoperability of BIM models with other systems using the open BIM concepts due to its flexibility and consistency of the IFC schema in the building lifecycle as one of the primary BIM enabling capabilities. However, the limitation of the IFC schema for operation and maintenance activity poses a problem to utilize the BIM with many O&M systems. Therefore, extensions to the current IFC schema to support the O&M activities are required. This IFC schema designed for operation and maintenance task were integrated by linking the BIM object's unique identifier (GUID) with other relevant data sources such as CMMS or AMS (Quaye, G.M, 2021).

(Heaton & Parlikad, 2020) propose developing an Asset Information Model (AIM) from IFC BIM models (Architect, structural, MEP), an external database that collect and host data from other sources. For the AIM integration, a functional-based classification system (UNIClass) is used for the decomposition of an asset from the project level to the component level. AIM relational database pulls data from BIM models and external data sources. Finally, AIM federated model is integrated and linked to the IFC BIM models, relational database, and point cloud data to form the digital twin platform.

Most of the buildings in Europe are constructed are before the 1970s when BIM models of the building did not exist. Therefore, for those buildings and infrastructure without BIM models, advanced technologies such as aerial photography, laser scanners, and photogrammetry techniques are used to capture the 3D building models using the Point cloud generated by advanced surveying equipment. These point cloud data are stitched to form the As-is BIM model (Peng et al., 2020).

3.3.2 Internet of Things (IOTs) and Sensors Technologies

The current practice of facility management in the O&M phase uses the BMS system such as BAS & CMMS system. These are proprietary software building management systems pre-programmed where the settings of sensors and alarms are preset on maximum and minimum threshold parameters. BMS systems are not designed for integrations of real-time operational data coming from multiple sources. This limit the capability of such a system to perform intelligent maintenance functions such as fault detections, and predictive & prescriptive maintenance (Lu et al., 2020b). However, with advancement in technologies like the internet of things (IoT), Wireless enabled sensors supports the collection and transmission of data from various sources. WSN allows data acquisition from distributed sensor networks through gateways and HTTP for monitoring and capturing the status of the physical environment and individual equipment within the system. Common usage of sensors in the operational phase of building includes monitoring and recording of the following parameters; indoor & outdoor temperature, relative humidity of the air, and equipment statuses such as speed, vibrations, temperatures, and pressure. (Lu et al., 2021) deployed following WSN abilities; to collect & upload data from diverse locations; can support a large number of assets allowing scalability and flexibility; affordable and readily available; perform analysis and control of resources and assets (Hallaji et al., 2022).

3.3.3 Big Data & Cloud Computing

One of the biggest challenges of adopting Digital twin in operation and maintenance stages is the huge volume of data (real-time data from sensors & user feed data by humans) coming from multiple sources (Peng, et al., 2020). Therefore, to handle the significant volume of data, big data services powered by open-source engines such as Amazon web service (AWS), Google Cloud, Microsoft Azure, Kafka, and Flink are necessary. DT process requires the continuous transmission and integration of sensor data from heterogeneous sources with a significant volume of both static and dynamic data flow. The big data analytics created at the backend consistently present high-density data streams due to their processing power to adapt quick-flowing data streams from multiple sensors (Lu, et al., 2019). Further, to increase performance, DT architecture should also incorporate big data and cloud computing.

3.3.4 Artificial Intelligence & Machine Learning Algorithms

Machine learning algorithms such as k-cluster are used for the detection of abnormal electric usage, Air handling unit defects can be predicted using long-term and short-term memory (LSTM), and open-source methods can be used to identify repair patterns that are repeated frequently. La Russa and Santagati (2020) used artificial data sets and multivariate linear regression-linked machine learning algorithms to create a Decision Support System (DSS). Unsupervised machine learning algorithms (statistical approaches) including Moving Average (MA), Cumulative Sum (CUSUM), and Binary Segmentation-based Change Point Identification Techniques were used to detect anomalies in environmental data. (Xie, et al., 2020). The higher maturity level of DT requires the capabilities of AI and ML to perform an intelligent predictive and prescriptive maintenance task.

3.4 Review of DT framework proposed for O&M stage

The findings from the literature review indicated, "Digital Twin is a concept rather than technology". Although the fundamental principles of using the DT concepts are the same throughout the industries irrespective of domains (aeronautical, manufacturing, and AEC sectors). The applications and architecture layers of DT are slightly different in the industry. The process design (framework) of DT concepts is significantly matured in most of the industries in contrast to the AEC industry. The manufacturing industry has already developed standards and guidelines for building DT.

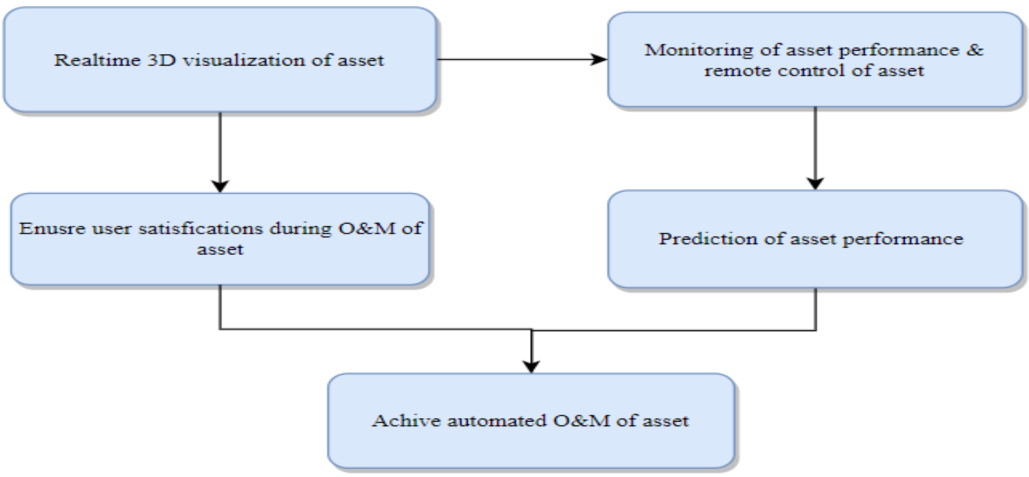


Figure 23. DT functions requirements for O&M (Own works)

Digital twin application in AEC industries is at the evolving stage and therefore the knowledge area is still at an early stage. Currently, there are no standards or guidelines to build DT in the AEC industry. Based on the stages of DT implementations, the information requirements and framework are developed in accordance with its purpose. In the O&M stage, although the DT architecture largely remains similar, many authors have proposed different methods of building DT architecture/frameworks based on their purpose. The application of DT in the O&M phase requires the integration of various enabling technologies such as IoT, BIM, VR, AR, big data, cloud computing, artificial intelligence, machine learning algorithms, etc. This section reviews the different frameworks proposed from the selected papers and synthesis the knowledge to build a foundation for implementing the DT in the O&M phase of building assets. The DT in the O&M phase should include the minimum basic aspects shown in figure 25.

The DT frameworks proposed for O&M of building asset systems are reviewed and analyzed;

DT Framework 1

This study analyzes present limitations and knowledge gaps in creating a dynamic DT at the building level from data management perspectives. Based on a case study conducted at the west Cambridge site. DT framework for developing dynamic DTs at building levels for the O&M phase is proposed. The DT architecture integrates heterogeneous data sources, with a data modeling layer to support intelligent data queries, and provides smarter decision-making processes. The framework proposed is based on five perspective system architectures shown below;

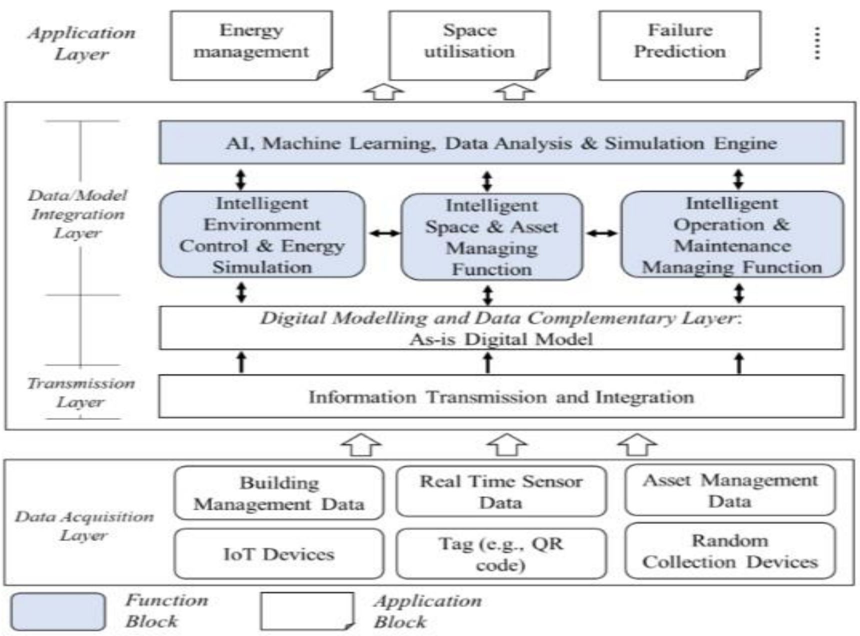


Figure 24. Dynamic DT framework for O&M of Building (Qiuchen Lu et al., 2019)

DT Framework 2

This framework proposes DT-enabled asset management in the O&M phase. The BIM limitations from the perspectives of both information richness and analytical capability in delivering efficient asset management were the primary motivation for developing this framework. The proposed framework uses smart asset management fundamentals and integrates DT technologies such as artificial intelligence, machine learning, and data analytics to create dynamic digital models that can learn and update the status of the physical counterpart from multiple information sources (Lu et al., 2021). The proposed hierarchical based architecture of the DT-enabled asset management framework for O&M is illustrated below;

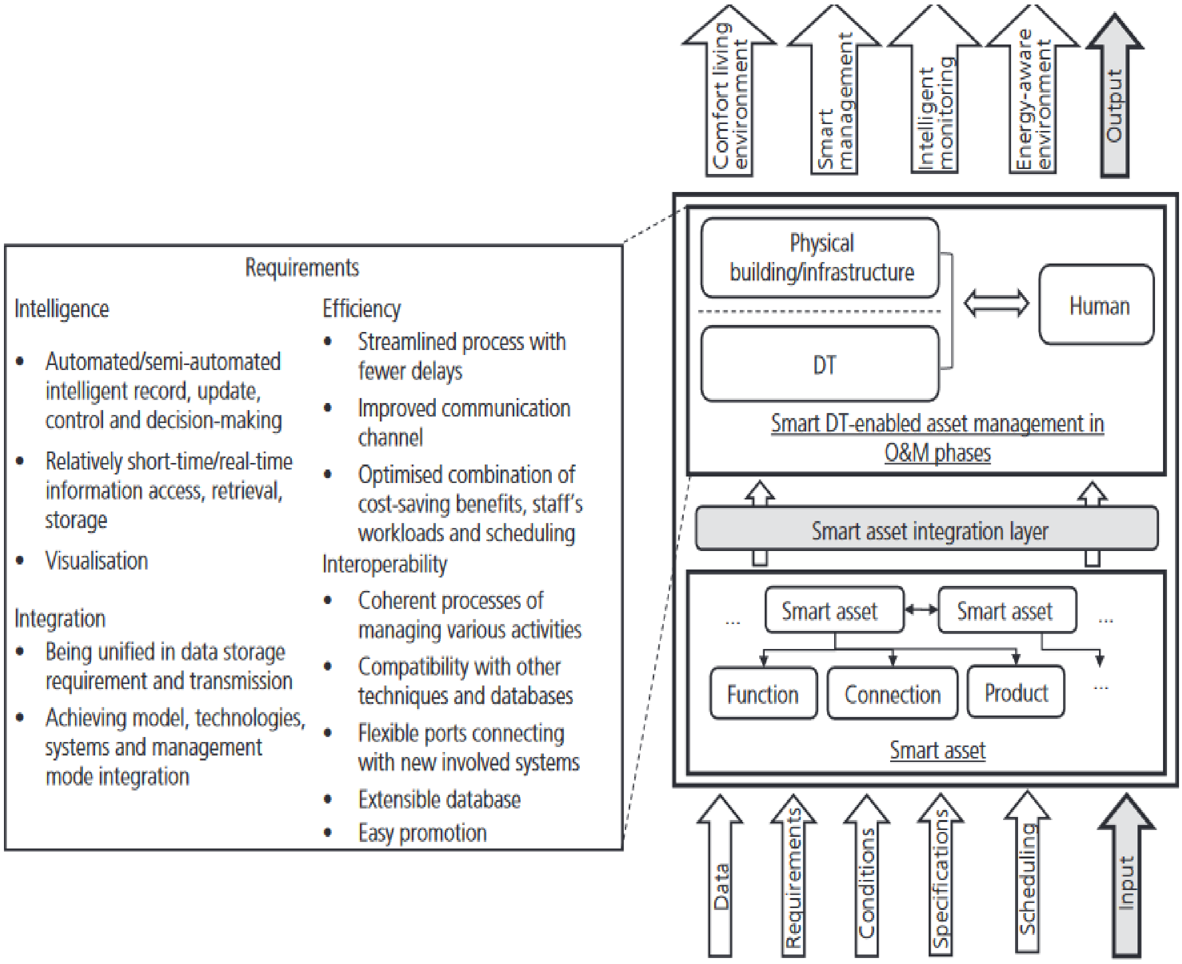


Figure 25. DT-enabled asset management framework (Lu et al., 2021)

DT Framework 3

This DT framework is the outcome of research titled "Digital twin-enabled anomaly detection for built asset monitoring in operation and maintenance" (Xie et al., 2020). The scope of this research is confined only to the component level for anomaly detections of a pump. This DT framework uses extended industry foundation classes (IFC) schema to integrate the operational and maintenance process for the building assets. The DT architectural layer for this framework remains same as framework 2.

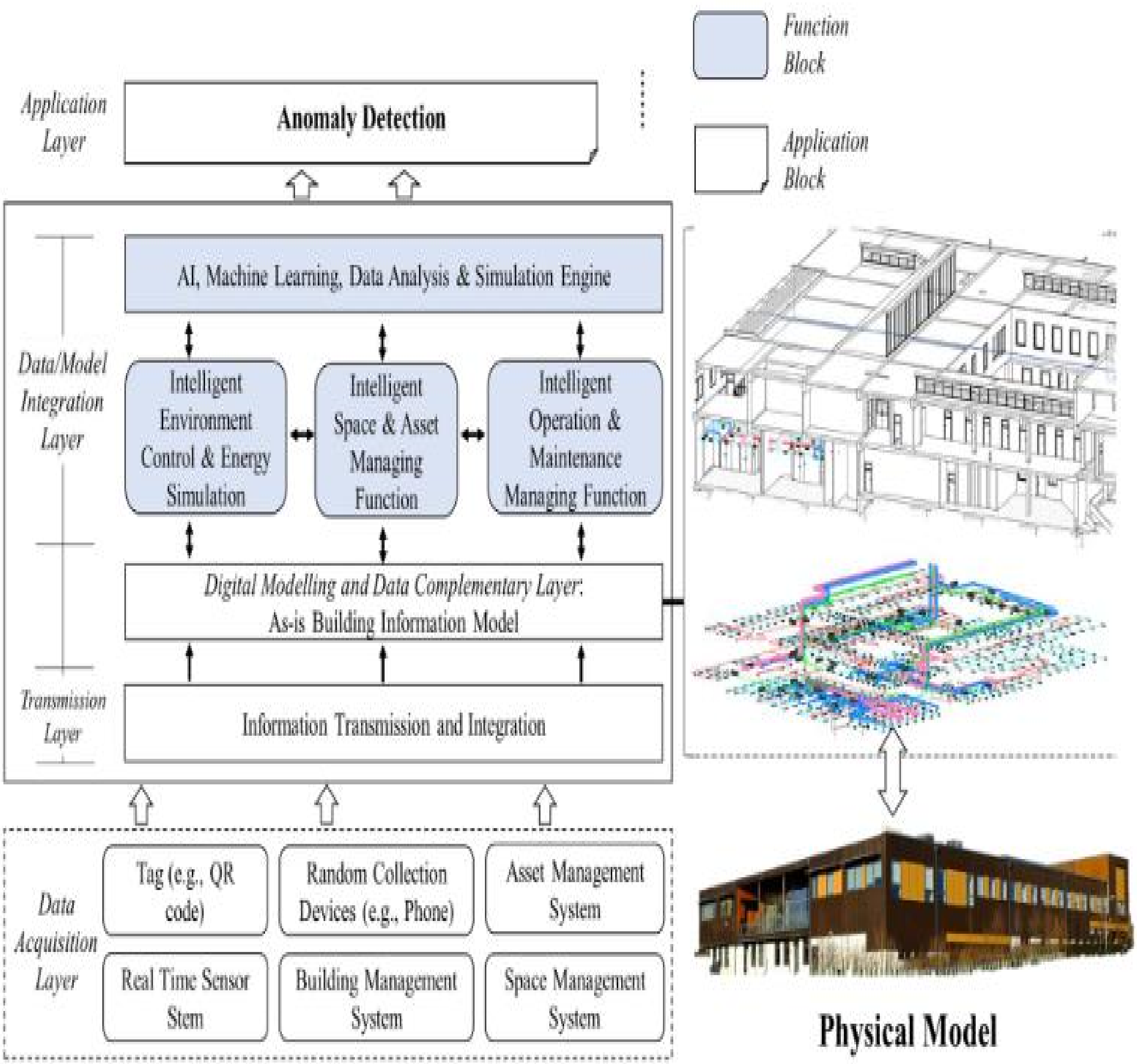


Figure 26. DT for anomaly detection of pump (Xie et al., 2020)

DT Framework – 4

(Zhao et al., 2022), proposed bottom-up approach for "Developing a conceptual framework for the application of digital twin technologies to revamp building operation and maintenance processes". The goal of this study is to promote the wider adoption of DT integration in the O&M phase by removing the constraints caused by the misalignment of the data integration and data standards. It offers facility management a bottom-up approach to DT implementation, covering the prerequisites, data collection from multiple sources, processing, transmission, and modeling, model integration layer with different intelligence tools, application, and data presentation layer.

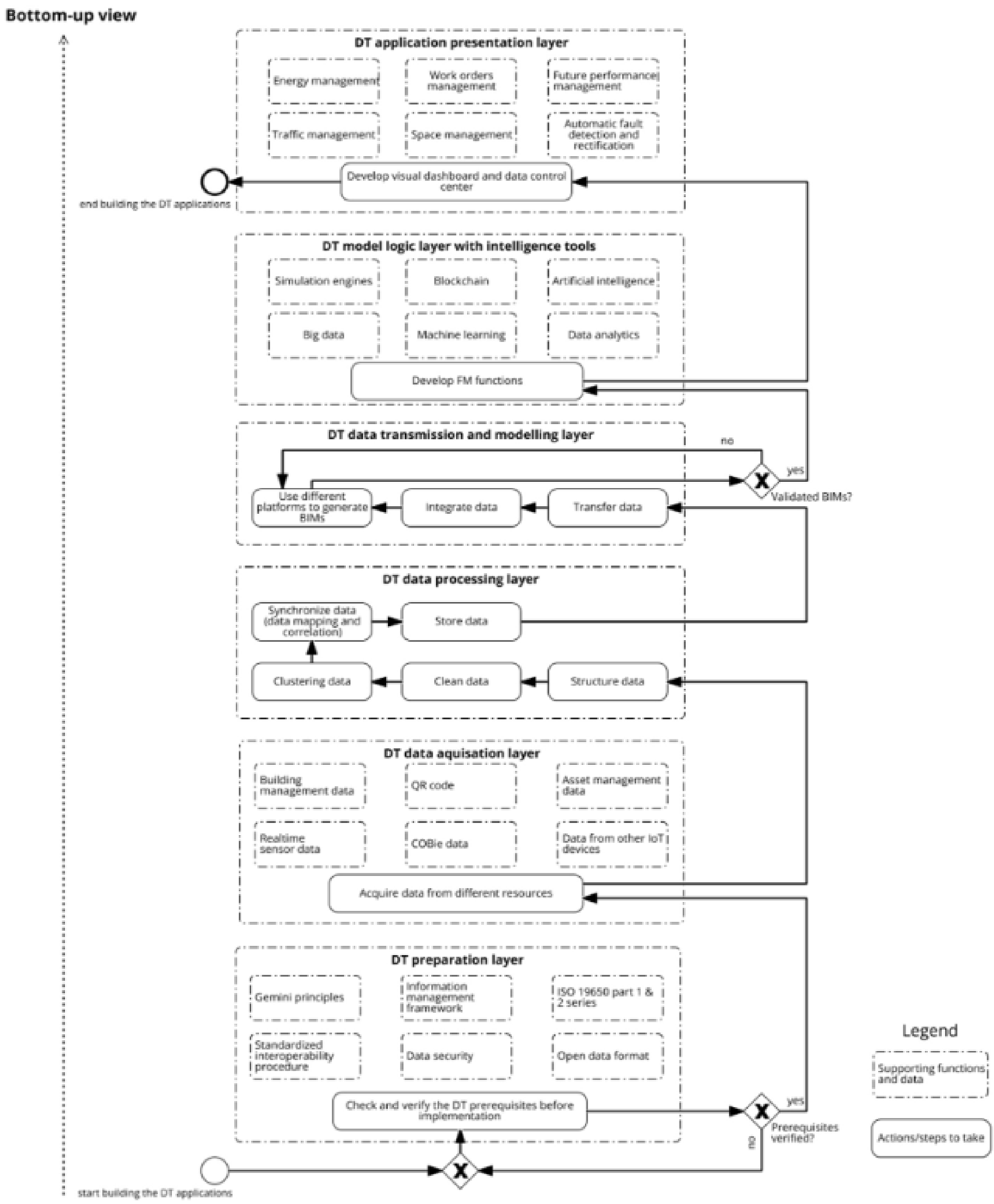


Figure 27. Conceptual Bottom-up DT framework (Zhao et al., 2022)

DT Framework – 5

(Quaye, G.M, 2021) proposed a DT framework for O&M of building systems based on the state-of-the-art research and expert consultations from the industry. The objective of the DT framework proposed is to improve the productivity of building lifecycle costs through optimizing the operation and maintenance activity. The DT architecture layers comprise five layers, data acquisition, data transmission, data integration & modeling, and prediction and automation layers.

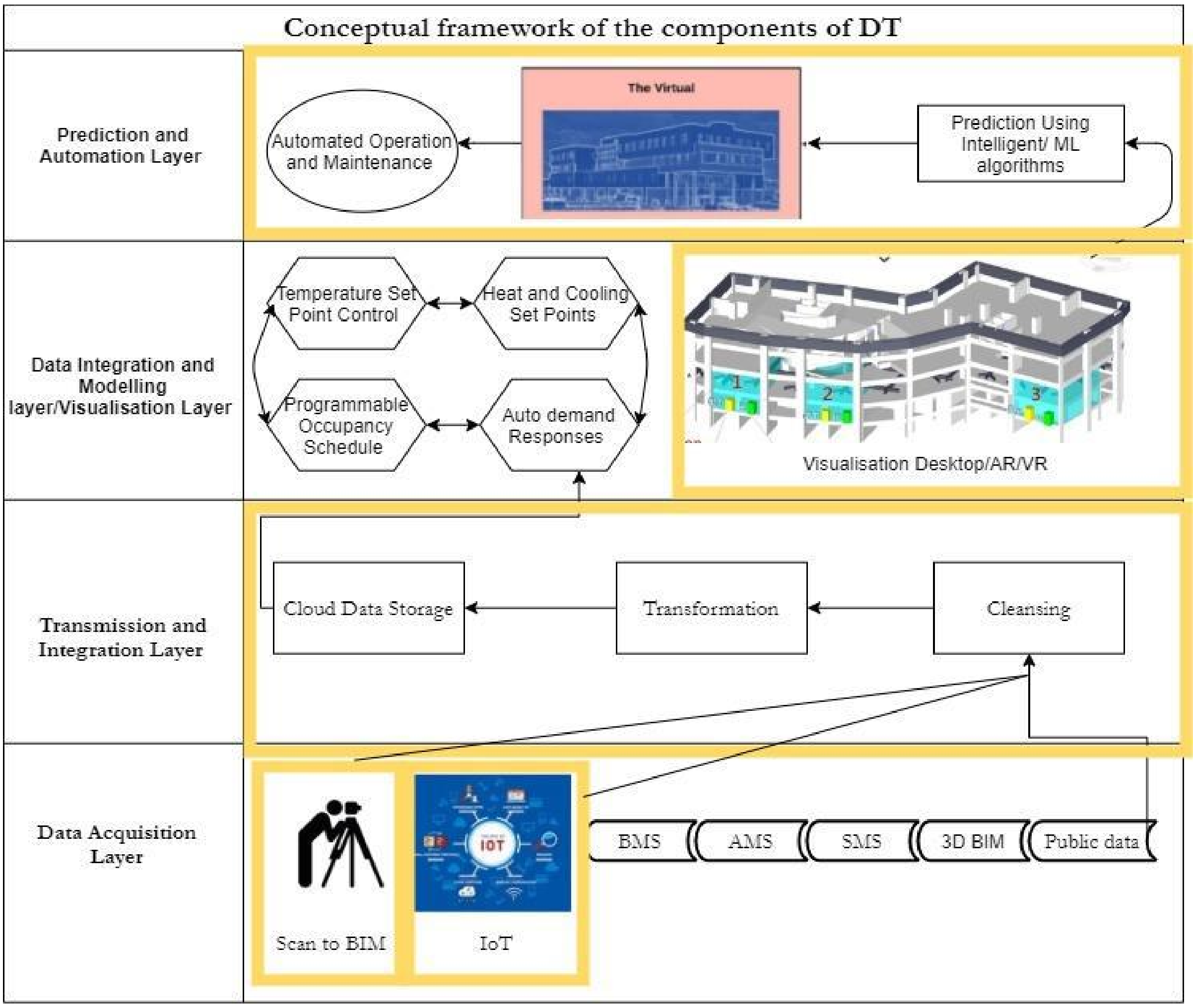


Figure 28.General DT framework for O&M phase (Quaye, G.M, 2021)

Table 5. Qualitative analysis of DT framework

Frame work	Application	Function supported	Real time data collections	Decision making	Predictive maintenance	Cost Reductions
Fr - 1	Building level DT for data management aligning to Gemini Principles	1-7	✓	✓	✓	X
Fr - 2	DT enabled smart asset management	1,2-7	✓	✓	X	✓
Fr - 3	Asset anomaly detections using DT in FM	3,4,6	✓	✓	✓	X
Fr - 4	DT driven FM using data integrations	1,2	X	✓	✓	X
Fr - 5	Optimization of O&M using DT framework	2,5	X	✓	X	X

Note: a. '✓' parameter fully reflected in the use case; 'Parameter partially reflected in the use case; and '×'parameter not reflected in the use case; b. Functions:1. DT management throughout the building lifecycle; 2. Data integration and information management to support decision making; 3. Various types of fault detection through sensors in MEP systems; 4. Secured real-time static and dynamic data exchange between the virtual and physical model of the building; 5. Data gathering from different types of equipment for maintaining a common data space and easier to access; 6. Predictive maintenance of the assets within the building; and 7. Automatic repair and maintenance request management system for FM professionals.

Since the DT is a concept rather than a technology, There is no standard process to develop the DT for every instance. DT architecture in the O&M phase depends on the objectives of its applications. Additionally, there are no standard guidelines available to evaluate the DT framework qualitatively or quantitatively. Nevertheless, there are many similarities and best practices in terms of DT architecture proposed for different application areas for the O&M phase. The components required for creating DT in the O&M stage at the building level are summarized below;

Table 6.. Summary of DT components for O&M phase (Own work)

Architecture layer	**Descriptions of requirements**	**Technologies deployed**
Data Acquisition Layer	Collect data from the distributed physical assets and the external environment. Data acquired are geometric information, environmental conditions, scheduling, and functional parameters Data types Building management data, real-time sensor data, asset management data, Tag (QR codes), and IoT devices	IoT-enabled wireless sensor network (WSN) for data collection from distributed assets. Scan-to-BIM technology, photogrammetry, laser scanners, aerial drone photography, or point cloud. My Structured Query Language (MySQL)
Transmission & Integration Layer	Transmit data from the physical asset to the digital counterpart and vice versa.	Transmission technologies widely used are WiFi, NFC, Bluetooth, 4G, WAN etc. Google Cloud, Amazon Web Services (AWS), and Microsoft Azure for transforming, processing, and storing data. Extract Transformation Load (ETL) technologies are used
Data Integration, Data Modelling & Visualization Layer	Kernel of DT architecture - This layer performs data and model integration and processing functions etc.	IFC, Forge (API), web-based program, Python, C#, and Java Script.

	This layer defines the digital replicas by integrating BIM, GIS, IoT sensors, asset management systems, weather data systems, cost, scheduling, and safety management platforms.	Visualization is performed through AR/VR technologies.
Prediction & automation Layer	In this layer information is generated by interpreting data, information is processed to create knowledge, and knowledge obtained ultimately supports decisions and actions.	Machine learning (ML) and artificial intelligence (AI). Long-Term and Short-Term Memory network algorithm.

4 METHODOLOGY FOR DEVELOPMENT OF DIGITAL TWIN FRAMEWORKS

This chapter deals with answering the key research question "Practical application of a framework for Digital Twins for O&M phases. To explain the steps and procedures involved in the development of the DT framework for the O&M phase of assets in the building project, The framework development process undertaken is illustrated in figure 31.

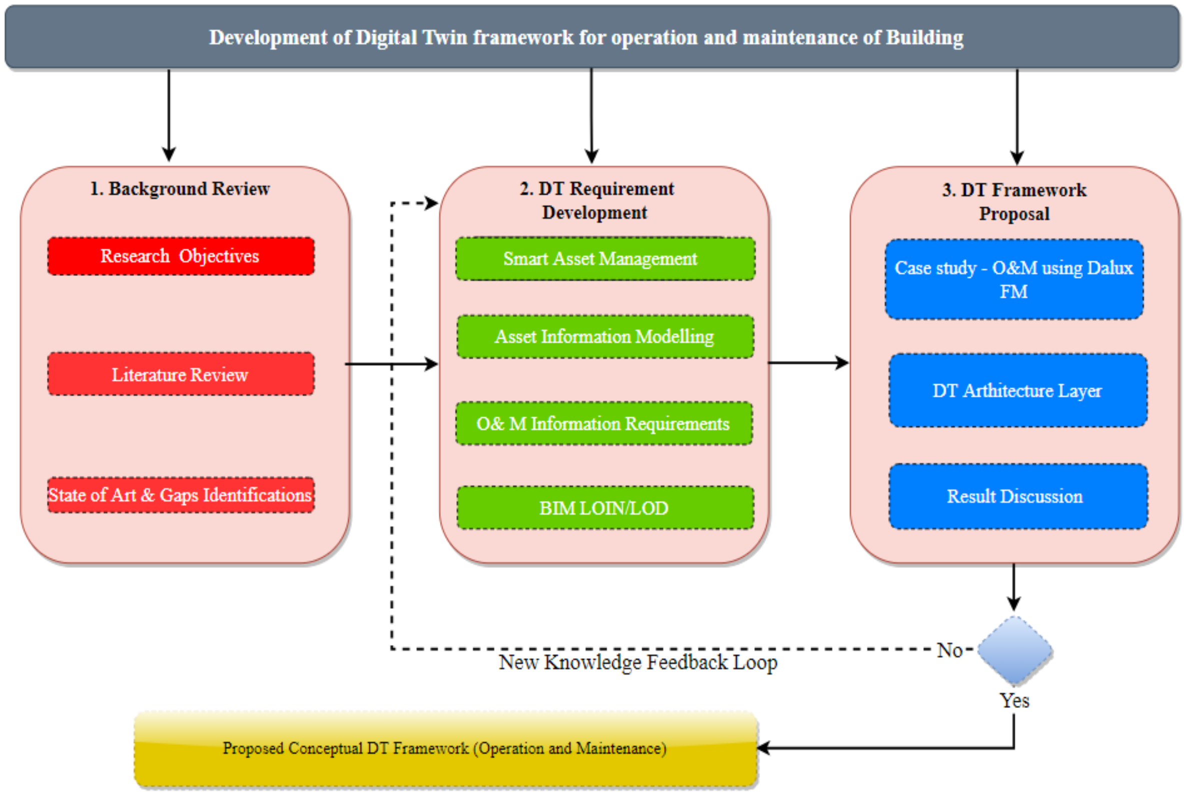


Figure 29. Development process of DT framework (Own works)

4.1 Background Review

The main research objective of this thesis is to propose the framework for the practical application of DT in O&M of building assets. Currently, the AEC sectors do not have unified standards, processes, and guidance documents for building DT for the O&M phase. BIM has proven its benefits in the building design and construction phase, However, BIM usage in the O&M phase has been limited due to its legacy format. The DT concepts and technologies available from industry 4.0 has enabled many AEC practitioners to harness the potential of the digital twin in the asset O&M areas. With the advancement of the digital revolution, the conventional ways of managing asset in the AEC industry has undergone radical improvement. However, owing to a lack of standard and guidance documents for building DT solutions in the AEC industry and also due to a lack of a unified process to implement the DT process.

The DT adoption rate within the AEC sectors for the O&M phase remains sluggish. Therefore to accelerate the adoption of DT in managing building assets during the O&M phase, the right level of DT architecture, a clear process of information requirements, and DT deployment are necessary. This chapter proposes the right level of DT framework for managing building assets during the O&M phase. The first task initiated for the development process of this framework is an exhaustive literature review which is already covered in the previous chapters. All the relevant DT concepts and architecture related to the O&M of building service are also reviewed and analyzed.

4.2 Development of DT Requirements - O&M Phase

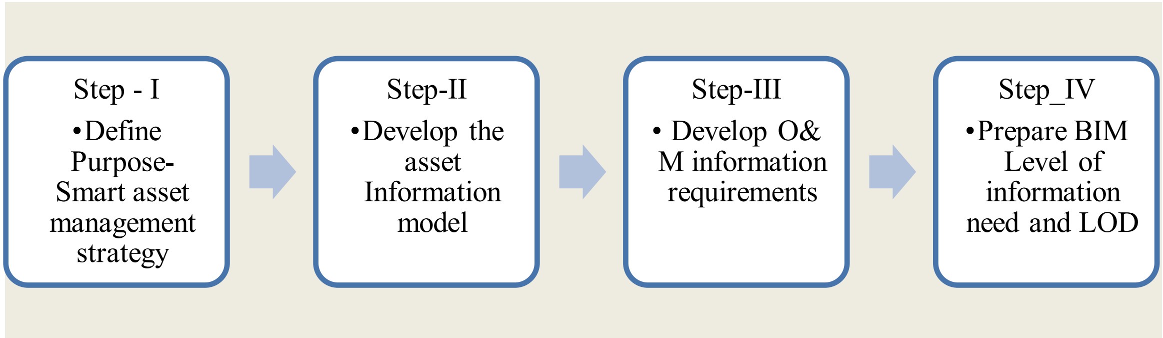


Figure 30. Development of DT information requirements process (Own work)

4.2.1 Smart asset management strategy

"Asset management refers to the coordinated effort made by an organization to generate value from the asset" (ISO 550001). According to IMM (Institute of asset management), a "SAMP is a planning tool to clarify intentions, priorities, and practices to be adopted". It takes a long-term view and considers the combination of organization needs, stakeholder expectations, and the conditions of existing assets and asset management capabilities”. Smart asset management refers to the ability to readily provide information about the asset, provide up-to-date asset performance and historical information, and generate knowledge based on advanced data analytics and decision-making.

The ultimate objective of asset management is to achieve the optimization of service, cost, and risk throughout the asset lifecycle. Research findings show that the O&M phase of any asset covers the majority of its lifespan and therefore accountable as a significant cost factor. The changing demographics and climate change have further aggravated the pressure on the built environment to improve the ways asset is managed. The environmental, social, and economic outcomes are changing at a rapid pace correspondingly. This has driven the world to rethink the current asset management process and make it more productive to adjust to the changing requirements. Effective asset management plays a significant role in delivering the functionality and serviceability of buildings.

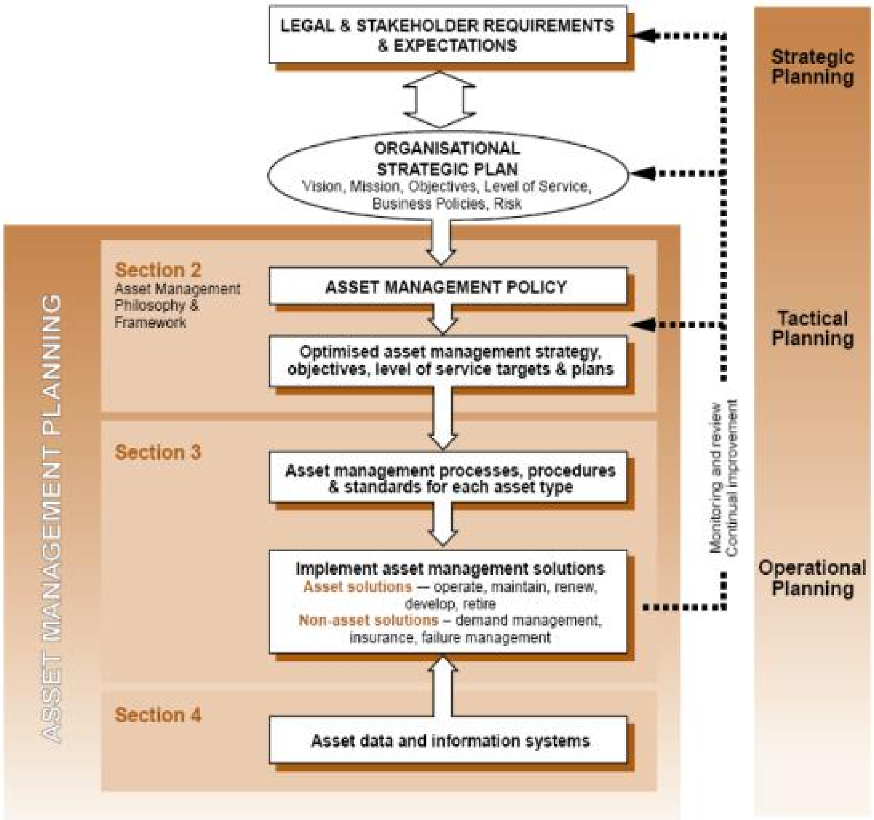


Figure 31. Strategic asset life cycle decision support system (IAM, 2022)

Therefore, it requires a coordinated shift in terms of cultural and technological paradigms to adjust to the changing requirements of the asset. Currently, there is a lack of holistic approaches and strategies to manage the asset and its associated information that can help to monitor, detect, record, and communicate operation and maintenance (O&M) issues. The digitalization of assets will enable better decision-making and asset value management (better design, selection, and delivery of new assets) through the usage of asset data such as behavior, and performance data (Papic and Cerovsek, 2019). Therefore, structured asset data is seen as the single most important parameter to achieving smart asset management. This data-driven asset management can transform from the current practice of siloed asset management to smart and connected asset management through the implementation of digital twin concepts and technologies.

(Papic and Cerovsek, 2019), proposed the 'Smart Asset Management Maturity' (SAMM) based on asset management requirements from various sources like the Institute of Asset Management (IAM) UK (2016), ISO 5500X series, the good practice developed by GFMAM (Global Forum on Maintenance and Asset Management), etc. Smart asset management concepts integrate all three dimensions of the organizational decision-making process, asset management principles, and technology management. SAM enables predictive and prescriptive approaches through real-time data integration. Smart Asset Management enables asset management organizations to make better decisions by working with up-to-date, true and reliable information using processes enabled by the latest technology. It is concentrated in various ways. The more efficiently information about assets is integrated, the more value you can derive from those assets (Papic and Cerovsek, 2019).

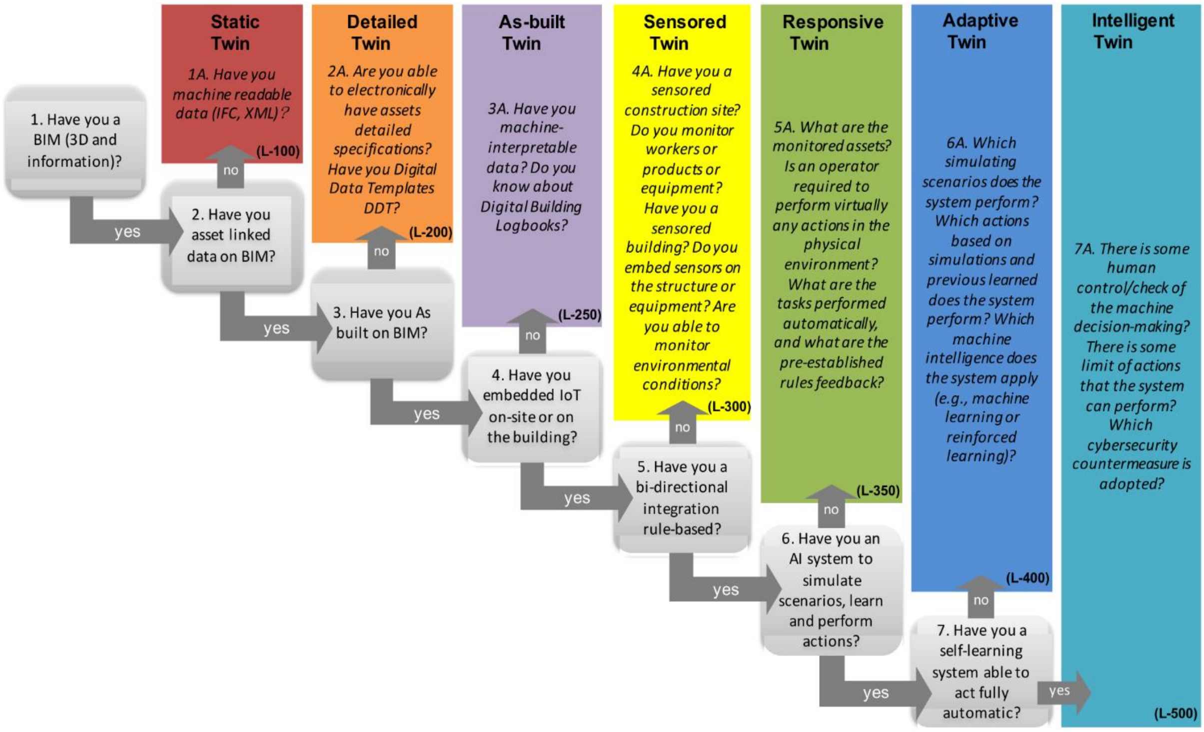


Figure 32. DT Incremental maturity level (Mêda et al., 2021)

The strategy of achieving the smart asset is governed by the asset performance requirement against the risk and cost. The decision support for choosing the right level of digitization should be based on the maturity level of the digital twin required. The corresponding cost associated with digital technologies implemented should justify the value gained (Measure objectives fulfillment against cost and risk). Therefore, choose the right level of digital twin maturity model before the adoption of DT.

4.2.2 Develop Asset Information Model

In the previous section, the significance of data or information is deemed as the lifeblood of the asset to create a digital twin in the O&M phase of building. This asset information is produced throughout the lifecycle of the asset at various points of time and undergoes continuous updates in real-time or periodically based on the level of complexity of the digital twin implemented. The data are produced and exchanged among the project stakeholders throughout the lifecycle to produce the asset information model (AIM) for the O&M phase. PAS 1192-3 defines AIM as "data and information that relates to the asset at a level required to support an organization's asset management system". This AIM is linked to various enterprise systems such as asset management systems, sensor systems, and physical environment parameters. Cobie data are derived from the Revit model during the BIM process and linked to the building asset management system such as BMS, CMMS & AMS for operation and maintenance functions. The process of information flow is illustrated below;

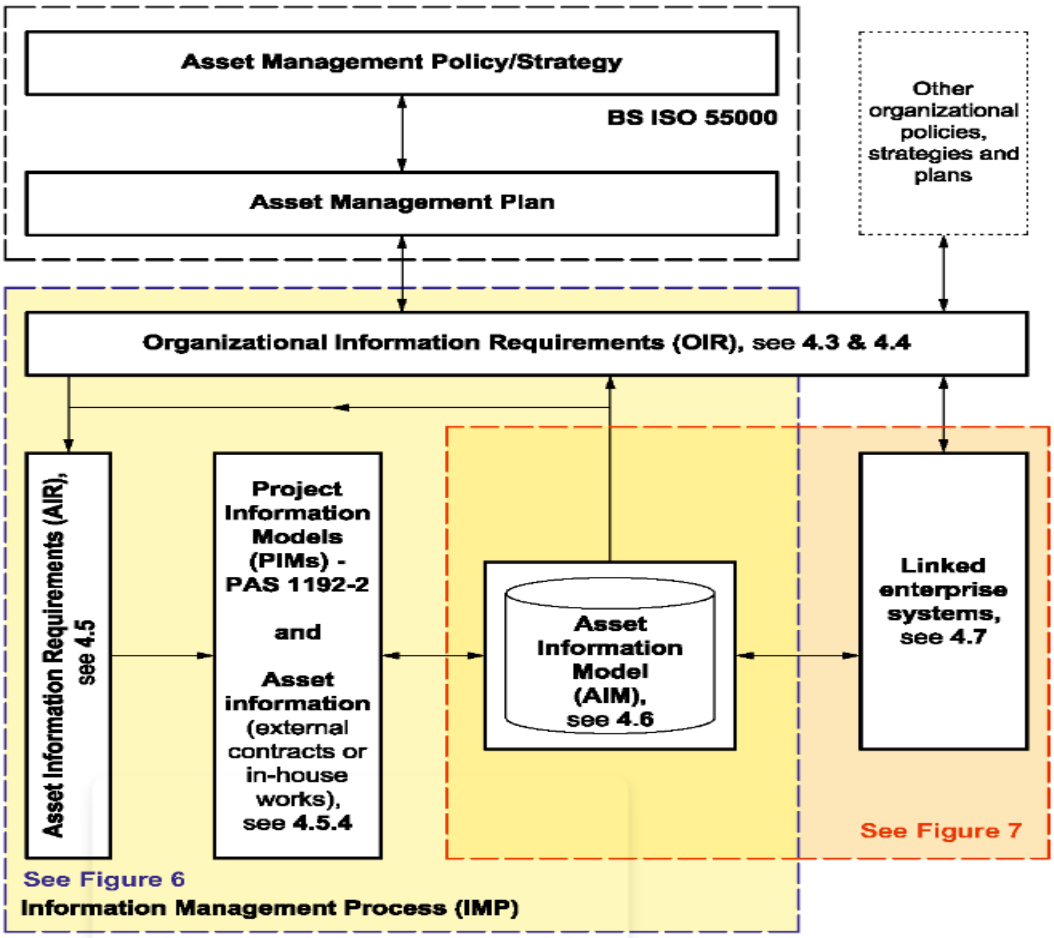


Figure 33. Asset information modeling process flow (ISO 55000-1, 2014)

There are many methods to produce the asset information model for the O&M phase depending on the building status. For a new building project, the Asset information model requirements are defined in the BIM execution plan (BEP) as per the information management process in figure 35. The information management within the BIM process is designed to produce, exchange, and collect the asset data in the required format, and passed to the downstream users for the fulfillment of the intended purpose. The BS EN ISO 19650 UK BIM framework guidance for the delivery phase and operational phase serves as guiding documents to produce the as-is asset information model;

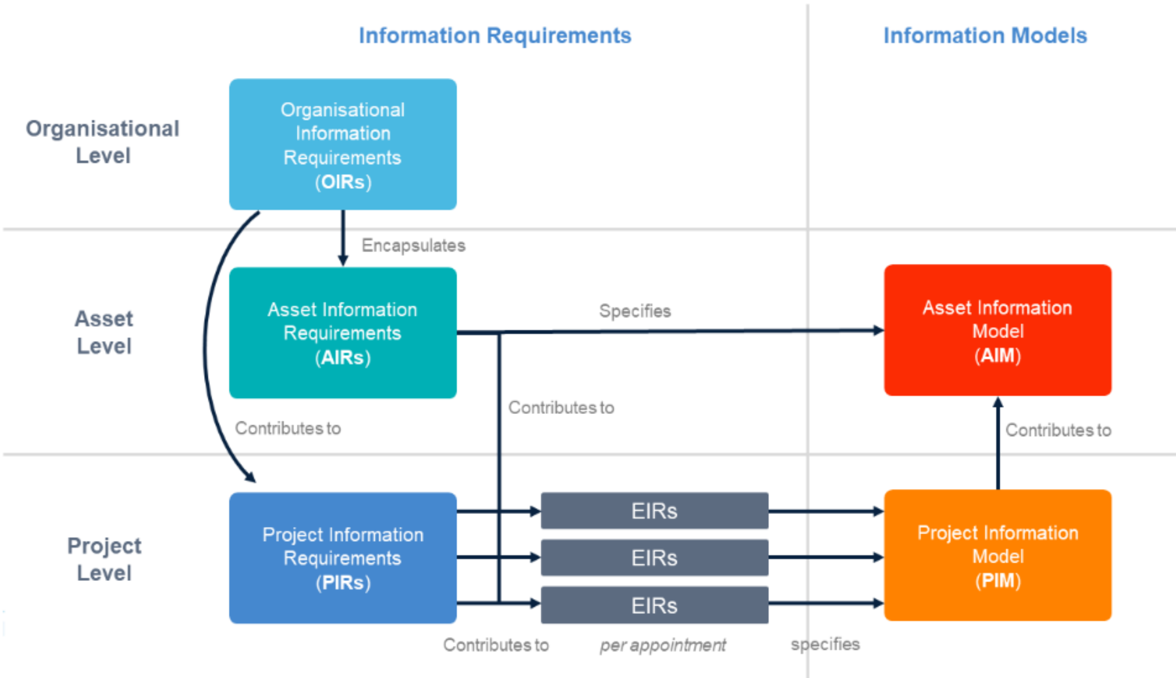


Figure 34. Information Exchange diagram (ISO 19650)

The common data environment (CDE) hosts all the structure and unstructured asset data produced during the project delivery phase. (The structured data are geometric data, alphanumeric, documentations, and unstructured data are images, photographs, and meeting notes). The CDE also hosts the O&M data produced and exchanged by various parties during the O&M phase. The CDE acts as a repository or a single source of truth for the asset.

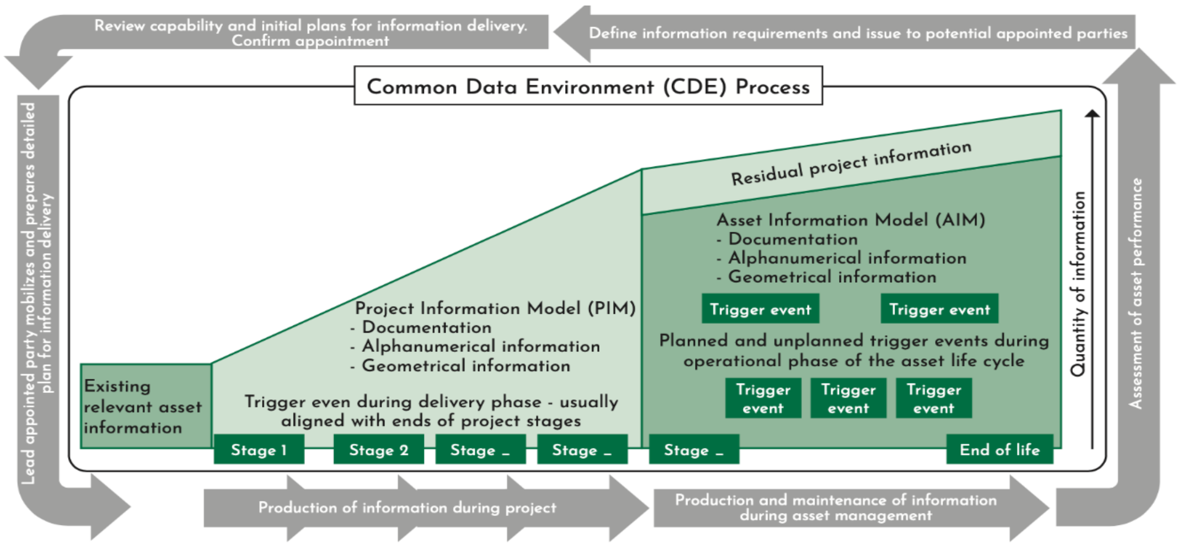


Figure 35. Information exchange process during the operation phase (ISO 19650)

For those existing assets without the BIM model or asset information model. Technologies such as laser scanning and photogrammetry are commonly used for producing the object-oriented model (geometric model) using point cloud data in Revit software. The non-geometric information of the assets system is updated based on the level of information needed by its purpose. The O&M data are either collected through user feedback or real-time data feed from sensors system integrated with the asset. According to (Heaton and Parlikad, 2020). The BIM IFC model quality is checked using the BIM collaboration format (BCF) and internal model mappings for the building level and room/space with the asset system and components are done using solibri model checker tools. The final approach after producing an asset information model requires the following steps to support the DT in the O&M phase (Heaton and Parlikad, 2020).

(1) Classification of assets within a BIM model, based on their functional output.
(2) Development of an AIM relational database, that is derived from an exported IFC model.
(3) BIM models linked to a relational database within a single federated model.

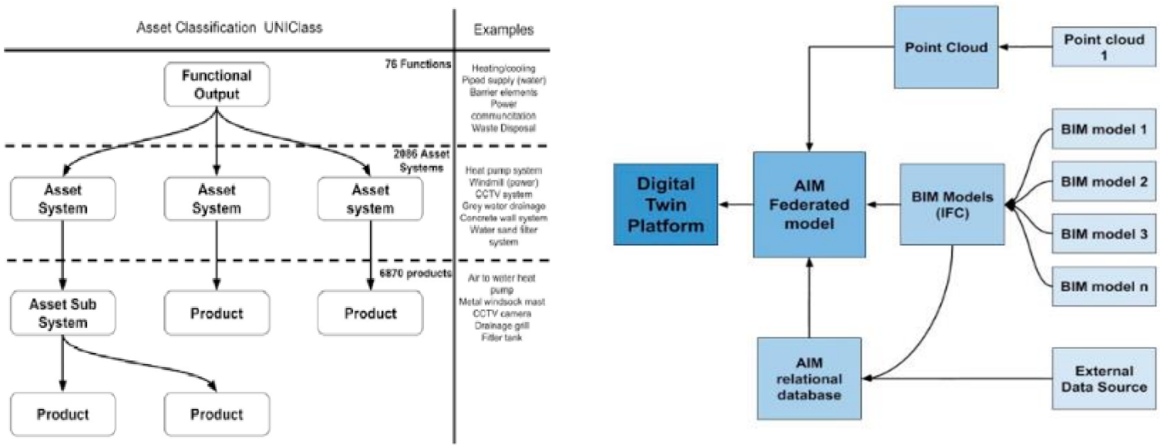


Figure 36. Asset classifications & AIM process for DT (Lu et al., 2021)

4.2.3 Develop O&M Information Requirements

One of the key aspects of DT architecture is data interoperability, integration, and data modeling. Dynamic DT of building assets in the O&M phase involves multi-domain and multi-layer information storage, manipulation, exchange, and interaction (Qiuchen Lu et al., 2019). O&M data stored in building information systems requires a significant amount of time to search, query, verify and analyze the corresponding facility information from heterogeneous data sources (Qiuchen Lu et al., 2019). Construction operation building information exchange data format (Cobie) is one of the common information exchange national standards adopted by the AEC industry for the integration of BIM and O&M systems. The Cobie allows the data exchange from the BIM model to CMMS, BMS, & AMS for the O&M phase. However, the Cobie spreadsheet can only represent partial O&M information and is therefore ineffective for creating adequate DT. The limitations are; model validation after the information exchange is needed; user-friendly information save and query approaches and formats are required; clear classification strategies of assets in O&M phases (e.g., sensors and control points) are needed to avoid misunderstanding of various O&M activities (Qiuchen Lu et al., 2019). These issues with the conventional approach highlight the need for an intelligent and comprehensive platform to integrate and efficiently search information, support decision-making, and promote automated and semi-automated procedures.

The other process to exchange the O&M information is using the industry foundation class (IFC). IFC schema is an open data format that supports a wider range of data exchange for interoperability. For effective integration of information to achieve smart asset management, a standardized, unified, open data schema is necessary for the O&M phase. IFC schema is flexible and the most suitable data schema for wider BIM implementation and information integration for the DT process. Therefore, a possible and effective solution for representing IFC schema and integrating information is to provide a centralized data model linking with distributed data resources in daily O&M management.

However, the existing IFC data schema for operation and maintenance does not support all the O&M events. There are no entities in the existing IFC 4 schema to specifically represent information and activities in O&M phases. Therefore, it is a prerequisite to developing missing IFC entities subclass, types, and parameters. Specific O&M processes and tasks involved for DT should be provided, and maintenance and inspection processes need to be defined. Following are some of the important new IFC entities required;

Table 7. IFC extension for O&M activity (Lu, Xie, Parlikad, et al., 2020)

	Inspection frequency and type	IfcTask			Sensor location	IfcPlacement/IfcSpace	
	Other maintenance required	IfcTask/IfcEvent			Identification code of target asset	IfcIdentifier	
	Maintenance cost	IfcCostItem			Asset name	IfcLabel	
	Est. maintenance date, real maintenance date	IfcTaskTime			The type of sensor	IfcSensorType	
	Contract code	IfcTask/IfcEvent			Timestamp of sensor	IfcTimeStamp	
	Accumulated depreciation		Spare sheet		Unit	IfcSensor	
	Source of components and spare parts				Description	IfcSensor	
	History record	IfcOwnerHistory/IfcPerformanceHistory	Record in sheets		Value	IfcSensor	
	Risk related to people or property	IfcProperty EnumeratedValue		Space management information	Organisation identifier	IfcIdentifier	Floor sheet Space sheet Zone sheet
Building management system	Site identifier	IfcSite	Facility sheet		Organisation name	IfcLabel	
	Site label	IfcSite			Site identifier and name	IfcSite	
	Node address/outstation number	IfcLabel	System sheet Component sheet		Building identifier and name	IfcBuilding	
	Outstation label	IfcLabel			Floor identifier and name	IfcBuilding Storey	
	Device response	IfcController			Room identifier and name, area	IfcSpace	
	Type of controller	IfcControllerTypeEnum			Room code	IfcSpace	
	Item label	IfcLabel			Occupancy activity, including identifier, occupier, occupancy time		
	Item units	IfcController					
	Power consumption	IfcTypeObjectProperty	Type sheet				
	Energy consumption and energy efficiency	IfcTypeObjectProperty			Record	IfcText	

O&M information requirements		IFC4	COBie 2.4 (spreadsheet xml)
Asset register information	Identification code/unique reference/barcode of asset	IfcIdentifier/IfcGloballyUniqueId	Component sheet
	Description of asset	IfcLabel/IfcText	
	Status of asset	IfcLabel	
	Type of asset		
	Serial number	IfcIdentifier	
	Placement/location	IfcPlacement/IfcSpace	
	Work manager, manufacturer, vendor	IfcPerson/IfcPerson AndOrganization	Type sheet
	Asset department	IfcOrganisation	
	Basic setting (e.g., output rating)	IfcLabel/IfcText	
	Category and code		
	Date of acquisition, installation or completion	IfcDateTime	Component sheet
	Permit-to-work requirement	IfcPermit	Job sheet
	Initial value, replacement cost, current value, disposal value, or written-down value	IfcCostValue	Job sheet
	Cost breakdown		
	Estimated Lifetime Remaining	IfcServiceLife	Type sheet
	Inspection or maintenance activity requirements	IfcTask/IfcEvent	Job sheet

O&M information requirements		IFC4	COBie 2.4 (spreadsheet xml)
Maintenance request related information	Placement/location	IfcPlacement/IfcSpace	Job sheet
	Call number	IfcLabel	
	Call description	IfcText	
	Call details	IfcText	
	Assigned to which category		
	Person in charge	IfcPerson	
	Contact information	IfcPersonAnd Organization	
	Identification code of target asset	IfcIdentifier	
Sensor system information	Location identification	IfcPlacement/IfcSpace	Component sheet Type sheet
	Location name	IfcLabel	
	Gateway identifier	IfcLabel	
	Gateway location	IfcPlacement/IfcSpace	
	Timestamp of gateway	IfcTimeStamp	
	Gateway type	IfcLabel	
	Sensor identifier	IfcLabel	
	Gateway ID which sensor mapped to	IfcLabel	

Other information required related to O&M activity are cost breakdown information of components and spare parts, historical records, maintenance cost, and maintenance activities This information cannot be directly linked with the asset information model (AIM) and therefore separately maintained and linked through the GUID. However, the IFC requirements can be eliminated using proprietary software such as Dalux FM, as this software has already integrated the O&M activity within their system.

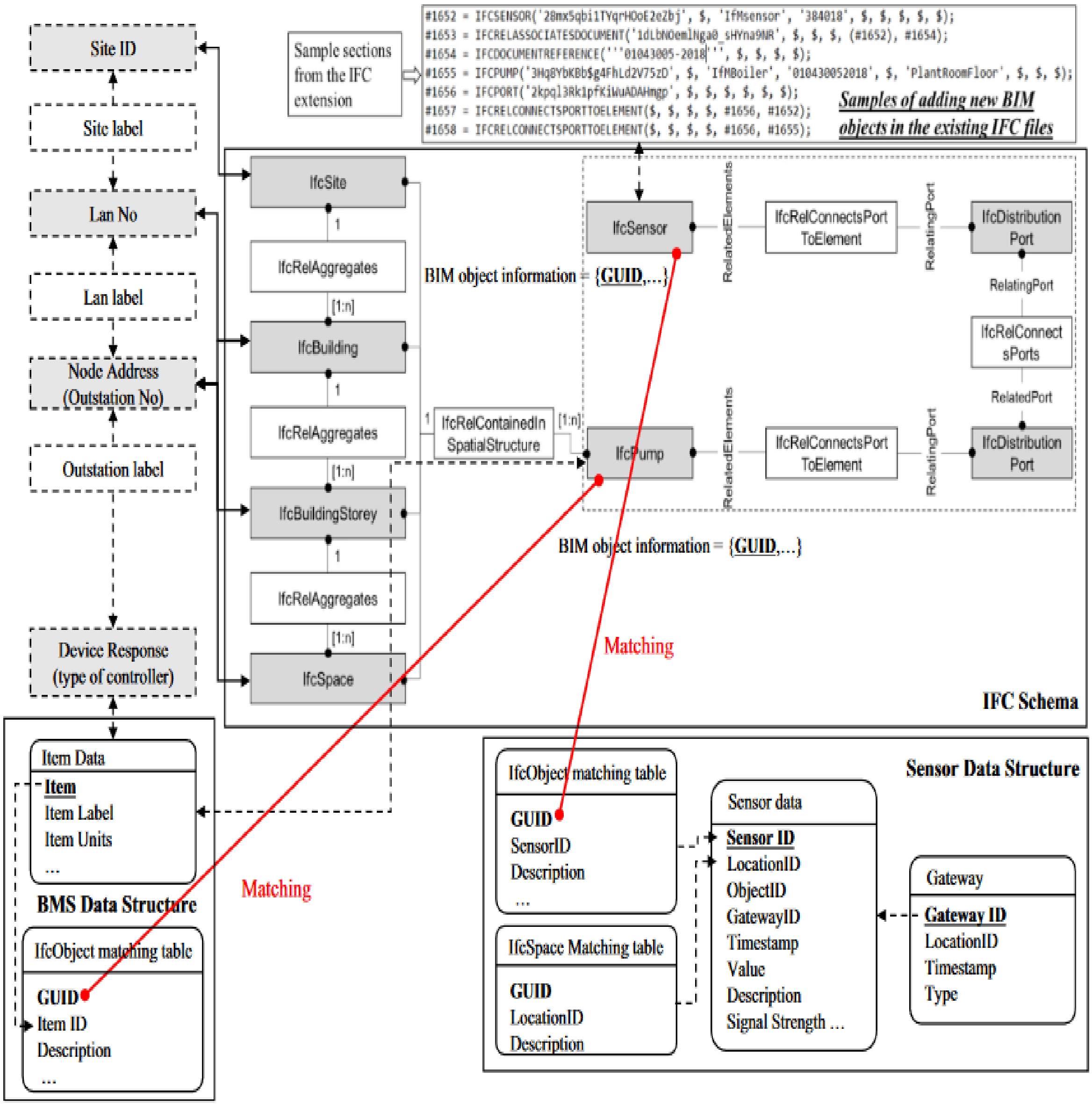


Figure 37. The IFC schema mapping with other data sources (BMS and sensor system) (Lu, Xie, Parlikad, et al., 2020)

4.2.4 BIM Model Requirement

The AEC industry follows diverse standards to develop information requirements in the absence of a common framework. The concepts of (LoD) level of details, (LOD) level of definition, and level of information have created more misunderstandings of the information requirements concepts rather than providing clarity. Several LOD specifications are published, and practitioners adopt the specification that best fits their understanding and established workflows, ideally as simple as possible and also flexible enough to precisely capture their information needs (Abualdenien and Borrmann, 2022). Therefore, to dispel the confusion created, the UK BIM framework has published the ISO 19650 – Part D specifically for developing the information requirements through the level of information need guidance (un-abbreviated). This level of information needed is further consolidated holistically in BS EN 17412-1:2020 for implementation. The information requirements for this part of the thesis are developed following the ISO 19650 (D) and BS EN 17412-1:2020 guidance.

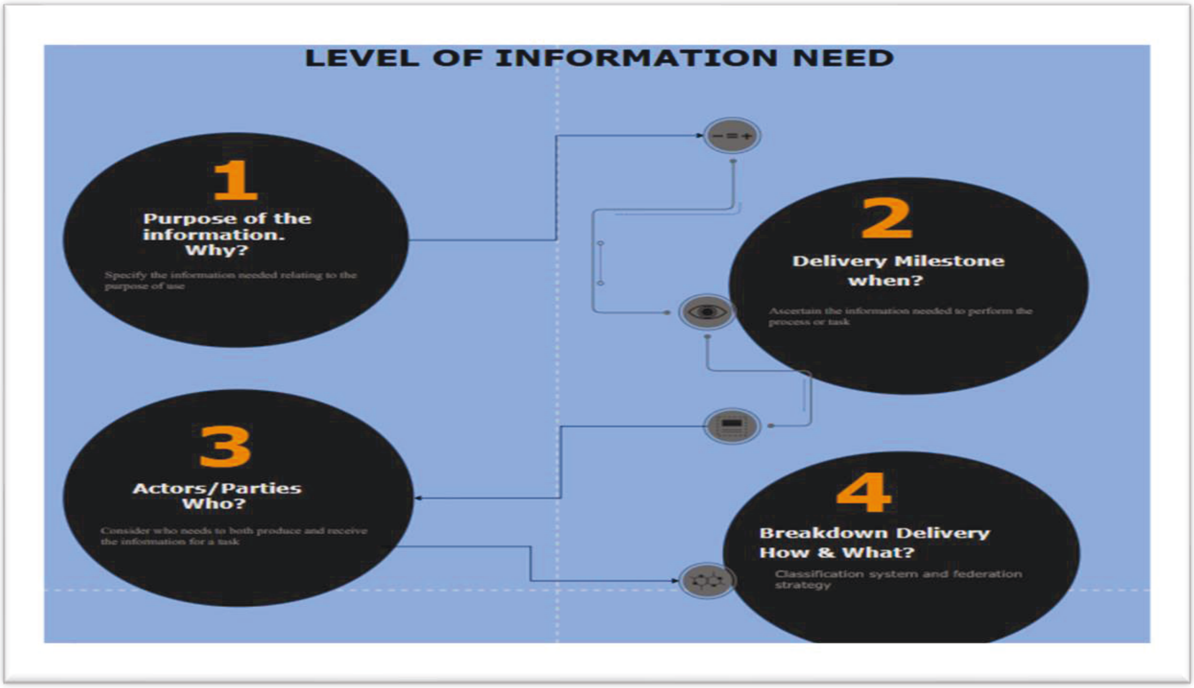


Figure 38. Level of information need framework (Own work)

According to the (UK framework BS EN ISO 19650), Part-D guidance documents, the fundamental purpose of the level of information need framework is to prevent the wastage of information across the lifecycle of an asset. The level of information needed is prepared based on what information (Geometric, Non-geometric, documents) is required by who (actors) and how (process), and when it should be delivered. According to ISO 19650 (Guidance part D), **"Level of information need" is a framework to define the quality, quantity, and granularity of information requirements**. The level of information needed is governed by its purpose, therefore, requiring different information deliverables for a different purpose.

The level of information need is defined by both appointing party (client) or in some exceptional cases by the lead appointing party (contractor) if the asset owner/client lacks the capacity. The level of information need is a framework for defining information across the facets (purpose, content, form, and format) (UK framework BS EN ISO 19650). The level of information need is defined across the following four sub-divisions to produce the Asset Information Model (AIM)

1. The purpose why information is needed
2. The Geometrical information to fulfill the purpose

3. The Alphanumerical information to fulfill the purpose
4. The Documentation to fulfill the purpose

Since the level of information need is purpose-driven, The good practice is to set the contextual background on which this information requirement is being developed (purpose).

4.2.5 Level of Information Need (LOIN) & LOD

According to ISO 19650 (D) for the level of information need, the information requirements are developed using the guidance table below for the operation and maintenance of the building. The level of information need is defined initially on the overall domain level (architectural, structural, MEP) rather than on the object/element/component level. However, for some components/objects, the level of information need is defined individually based on purpose govern by operation and maintenance requirements.

Table 8. LOIN - Architectural model

Information delivery Milestone	Operation and maintenance	
Purpose	Visualization/simulation/	
Actors	Lead appointed party	
• **Architectural Model**		
- Geometric information	Details	Simple, LOD = 300
	Dimensionality	3D
	Location	relative
	Appearance	realistic
	Parametric behavior	explicit geometry
- Alphanumeric Information	Identifications	classifications, uni class
	Information contents	dimensions, levels, story, space, zones
- Documentations		specifications of architectural components

Table 9. LOIN - Structural model

Information delivery Milestone	Operation and maintenance
Purpose	Visualization/simulation/
Actors	Lead appointed party

• **Structural Model**		
- Geometric information	Details	LOD 300
	Dimensionality	3D
	Location	reference
	Appearance	realistic
	Parametric behavior	explicit geometry
- Alphanumeric Information	Identifications	classifications - uni class
	Information contents	dimension, shape
- Documentations		specifications of structural components

Table 10. LOIN - MEP model

Information delivery Milestone	Operation and maintenance	
Purpose	Visualization/simulation/	
Actors	Lead appointed party	
• **MEP Model**		
- Geometric information	Details	Detailed - LOD 500
	Dimensionality	3D
	Location	Relative
	Appearance	Realistic
	Parametric behavior	Explicit geometry
- Alphanumeric Information	Identifications	Naming, numbering, classifications, reference structure (Cobie/IFC).
	Information contents	Tech spec, cost, manufacturer & supplier warranty information, design criteria installation date
- Documentations		Product specifications, maintenance manuals, operational manual

		Photographs, 2D diagram/system process

Table 11. Level of Details (LOD)

Identifications		**Geometrical Information**	**Alphanumeric Information**							
Element Class	IFC Class	LOD	Classifications	Name & Model no	Tech specs.	Vendors info	Cost information	Installation date	Performance	Cobie
Project	Ifcproject	200								
Site (property)	Ifcsite	200								
Building	Ifcbuilding	200								
Building Story (Floor)	Ifcfloor	200								
Space	Ifcspace	200								
elements	Ifcbuilding elements	350								
Chiller	Ifcchiller	350	×	×	×	×	×	×	×	×
Boiler	IfcBoiler	350	×	×	×	×	×	×	×	×
Condenser	Ifccondense r	350	×	×	×	×	×	×	×	×
Centrifugal Pump	Ifcpump	350	×	×	×	×	×	×	×	×
Filter	Ifcfilter	350	×	×	×	×	×	×	×	×
Grilles	Ifcelements	350	×	×	×	×	×	×	×	×
Dampers	Ifcelements	350	×	×	×	×	×	×	×	×
Ducts	Ifcducts	350	×	×	×	×	×	×	×	×
Pressure sensor	Ifcelements	350	×	×	×	×	×	×	×	×
Temperature sensor	Ifcelements	350	×	×	×	×	×	×	×	×
Thermostat	Ifcelements	350	×	×	×	×	×	×	×	×

4.3 DT Framework Development

4.3.1 Case Study

The case study was conducted for the Faculty of Medicine main building located at the Vrazov trg, University of Ljubljana, Slovenia. The estate includes 1 main and one annex building (3 stories) covering a 250 Sqm area comprising of the lecture room, laboratory space, faculty office, research and laboratory space with individual LOTS (parking, flower garden, etc).

In line with the dissertation objectives, the case study is required to demonstrate the practical application of the DT framework in the O&M phase. Based on understanding and knowledge gained about digital twin concepts and frameworks through the literature review, It is conclusive that, implementing DT for the O&M phase demands skills and knowledge from various fields. Many companies are providing digital platforms to create DT solutions for the O&M of building service. Some of the major DT solution providers are Autodesk Tandem, Ecodomus/Siemens, Microdesk, and Archibus. Dalux FM is one of the proprietary software platforms developed specifically for the O&M phase of building. For this case study, the Dalux FM platform is used for the demonstration of the DT solution for maintenance of the ventilation system in the building project identified for the case study.

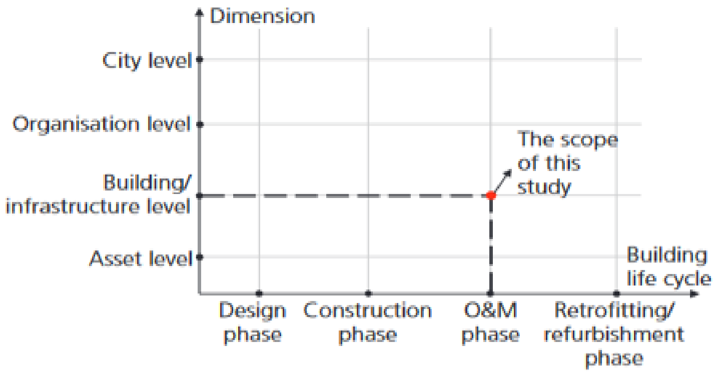


Figure 39. Scope of a case study (Own works)

Dalux FM platform is one of the established DT solutions built for O&M of building. The cloud-based platform provides a comprehensive DT solution to perform user-defined O&M processes based on the types of assets to be maintained. This platform integrates all the necessary DT architecture required to perform O&M activity within its system. The DT implementation process for O&M of the ventilation system in the building, using the Dalux FM is illustrated in sequence hereunder;

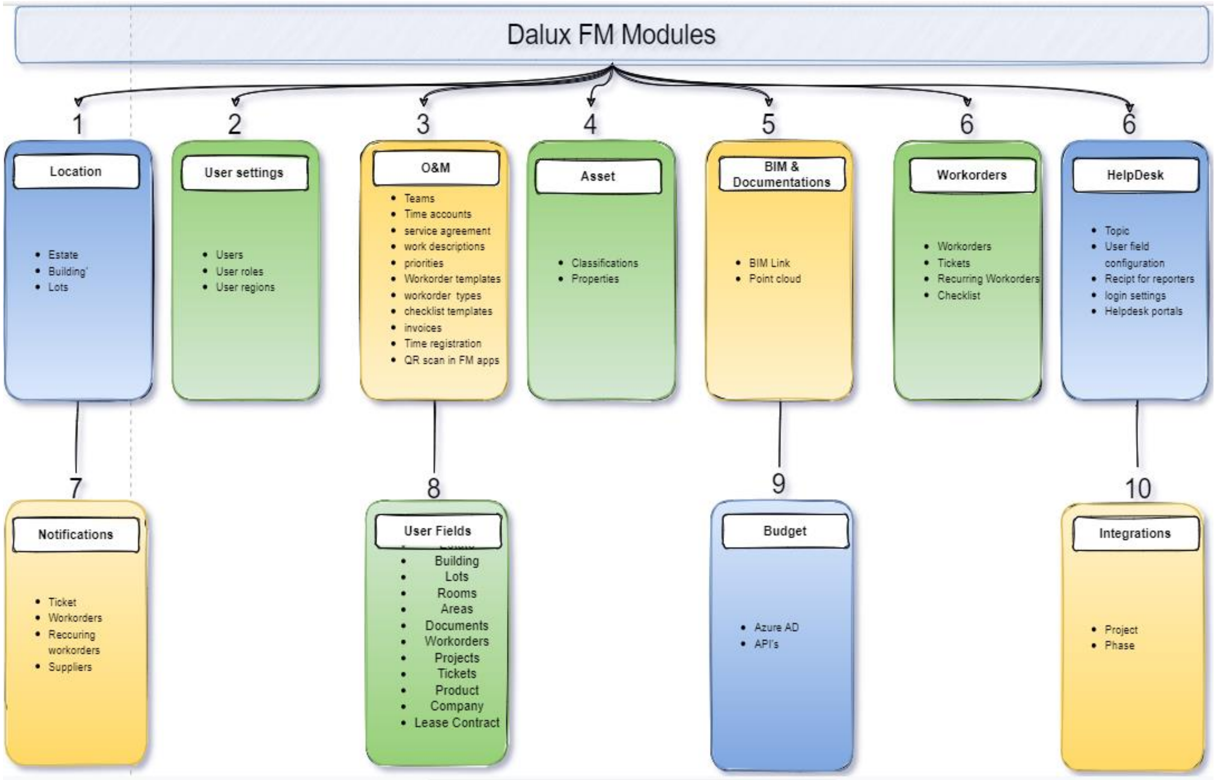
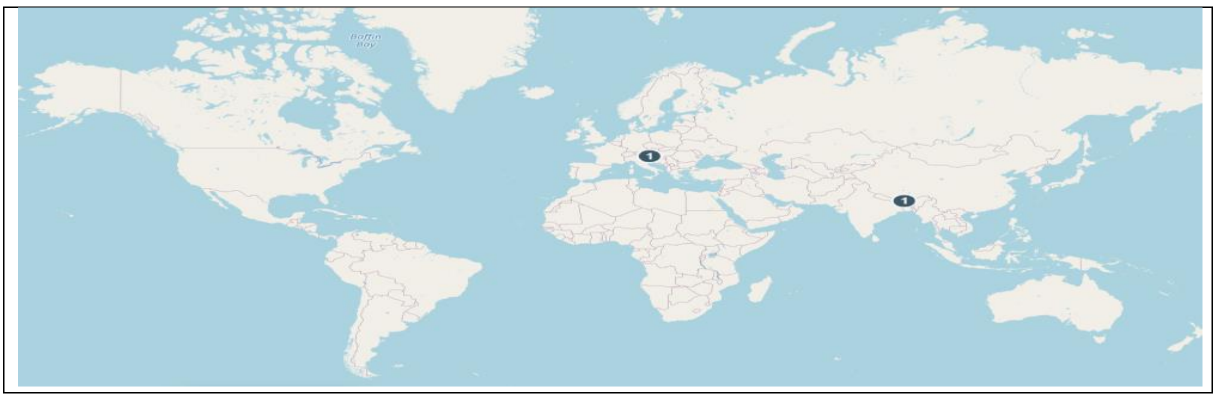


Figure 40. Dalux FM modules (Own work)

1. Location Modules

Based on the strategic asset management plan, the maintenance requirements are decided for each of the asset portfolios. Dalux FM supports managing the asset located in various locations and regions from one platform. The foremost process is to identify the geo-location of all the estate, buildings, and Lots within the scope of the maintenance plan. The geographical information system (GIS) features are integrated with the software platform to allow identifying and marking the exact location of each building included in the maintenance project as shown in figure 45. The building system and components are positioned relatively to their exact geocoordinates.



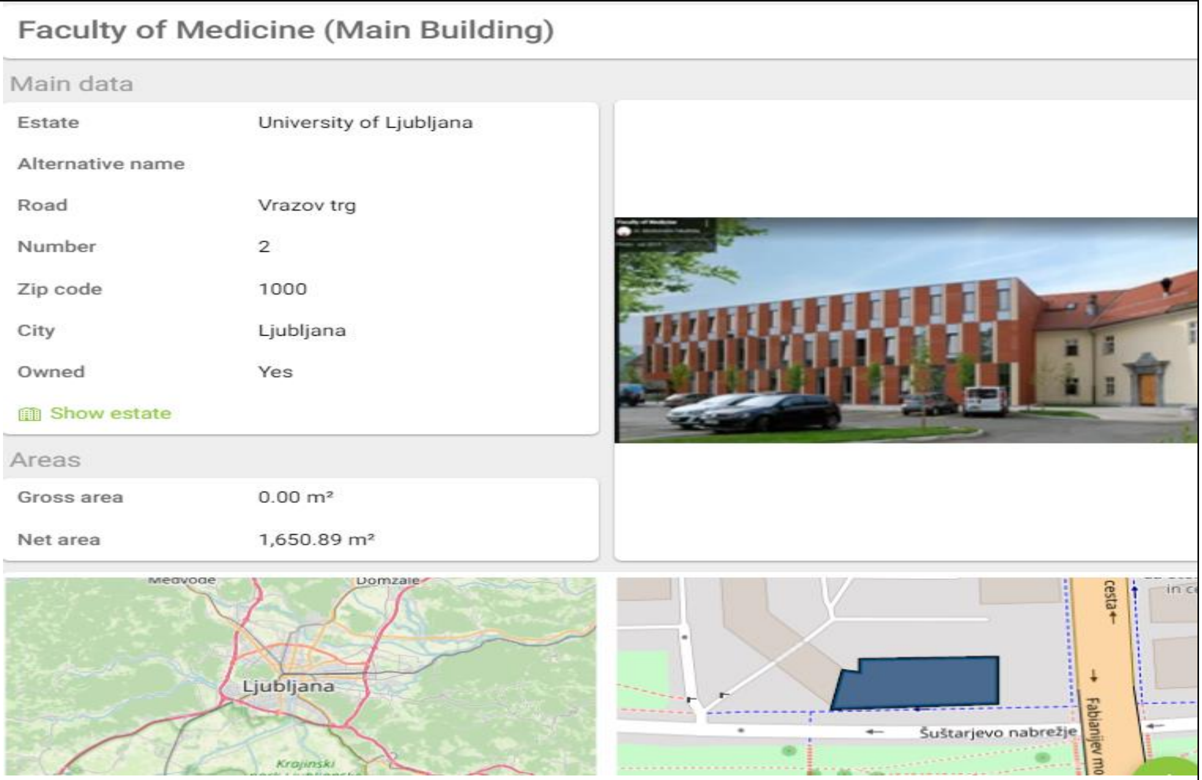


Figure 41. Geolocation of project & building in location modules

For any DT preparation, the BIM model or object-oriented model is essential. Based on the overall purpose of DT implementation, This BIM model of the building, system & components is prepared as per the level of information need (LION) and LOD. Prior quality check of all the relevant BIM models (IFC format) is performed using configured rulesets to remove any discrepancies and inconsistencies using solibri model checker. This includes clash detections within the same models and with other disciplines. The critical parameters required in the BIM models are mapped and grouped using solibri model checker. The metadata required for each component is also checked and ensures fulfillment. The IFC output file from solibri is uploaded to the Dalux platform location modules, and 3D models (architectural, structural, and MEP model) are uploaded and linked to the room and space of the building footprint on its geolocation. 2D drawings of each floor are also placed corresponding to the floor system of the building. Other project-related documents relevant to the maintenance activity of this building are also uploaded and linked to individual systems and components. The uploading of the BIM model, Autocad drawings, processing, and mapping is done within the Dalux FM.

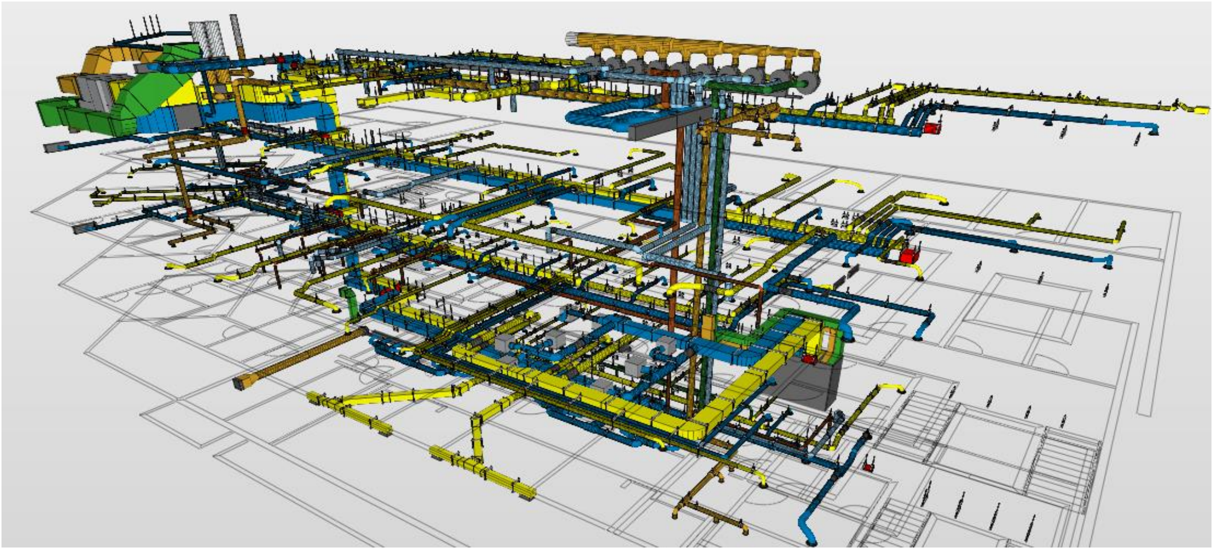


Figure 42. MEP model of building

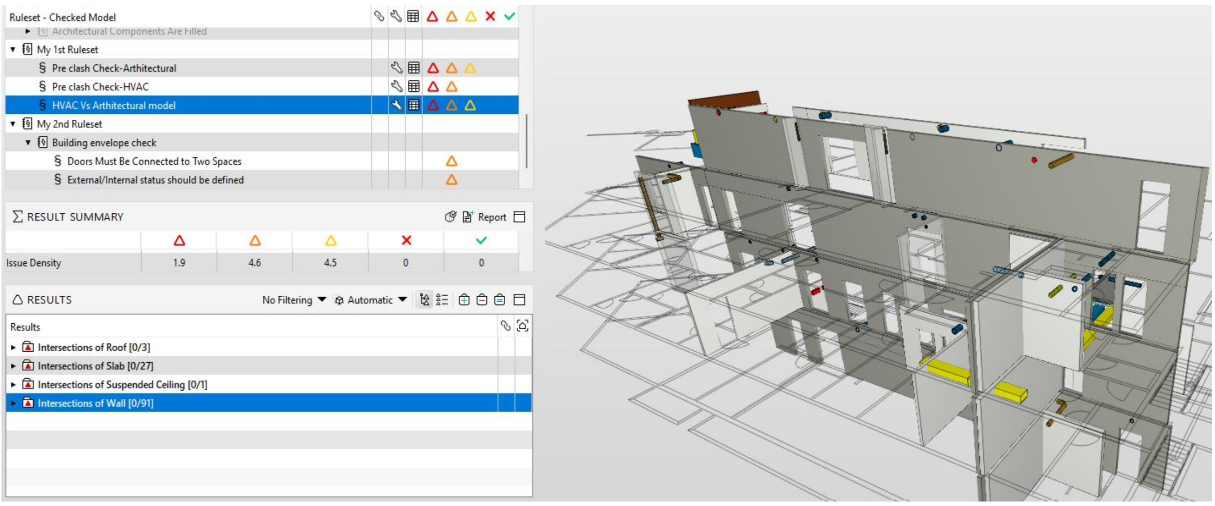


Figure 43. Solibri ruleset for clash and building envelope check (solibri office)

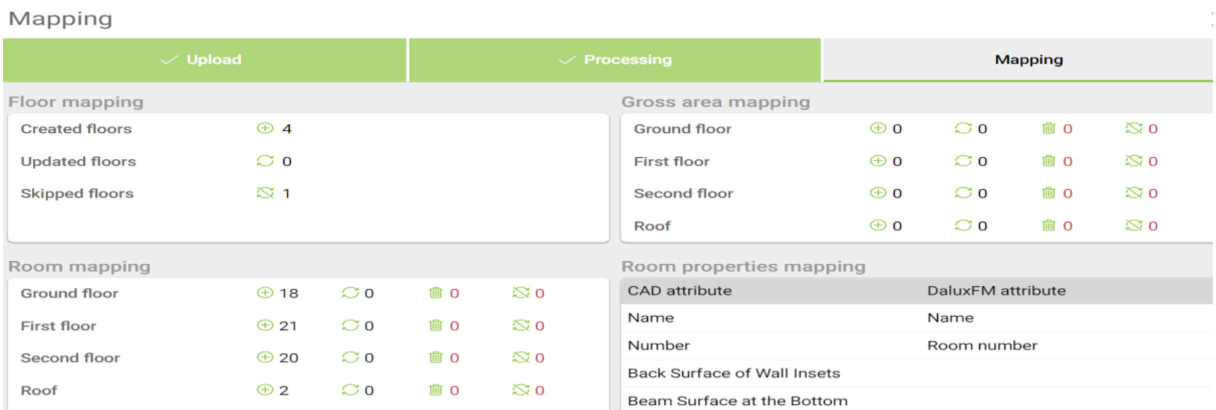


Figure 44. Uploading, and processing mapping of floor in Dalux FM

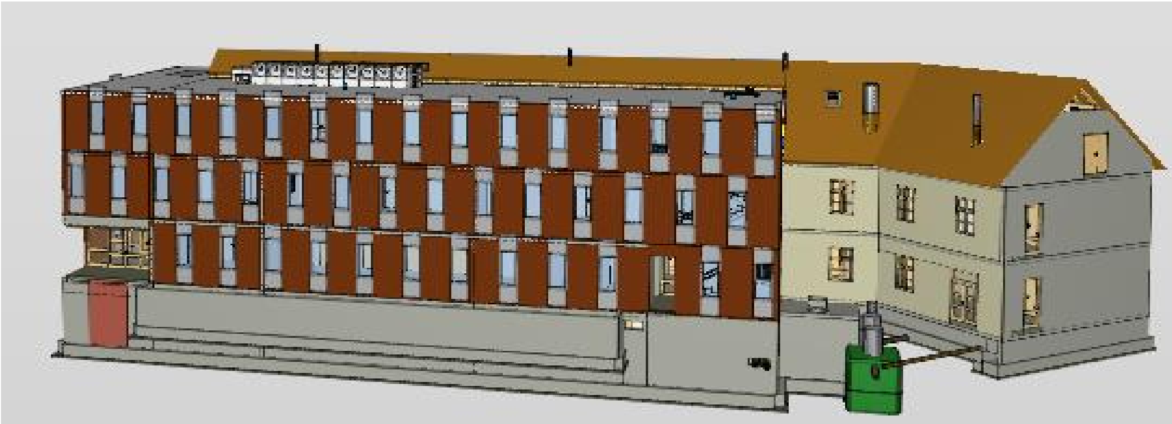


Figure 45. Federated 3D BIM Models (architectural, structural, and ventilation models)

Figure 46. Dalux FM Interactive 2D and 3D visualization - (Dalux FM)

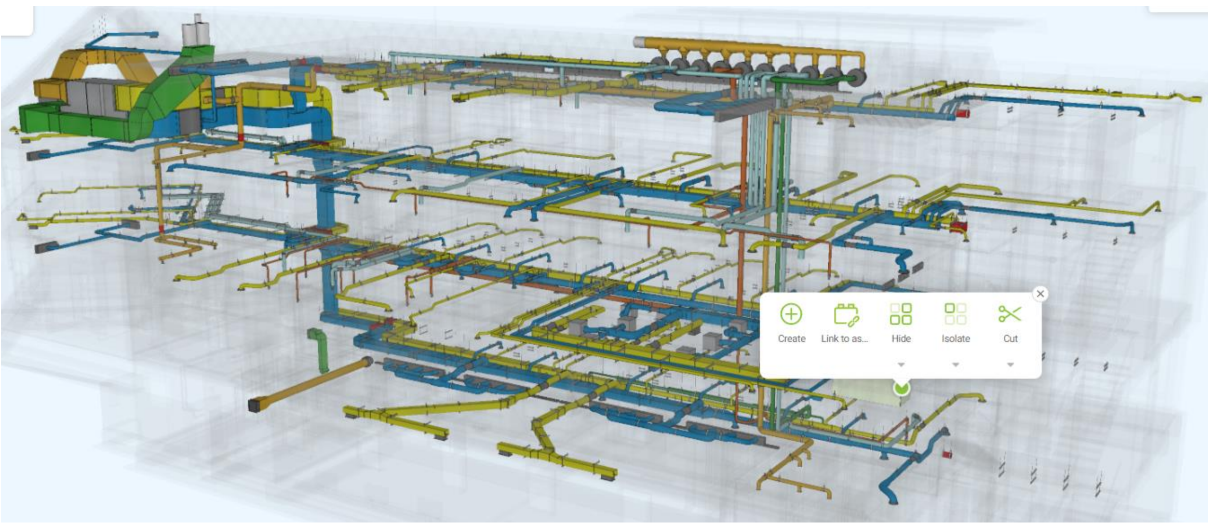


Figure 47. The ventilation system of the building (Dalux FM)

2. User Settings

The maintenance process involves multiple stakeholders for the O&M process. The Dalux FM user setting module support user definitions which include user identity email ID as the primary key and secondary keys include user roles & responsibilities (owner, estate manager, maintenance personnel, supplier, contractor, manufacturer, account, and budget), the scope of responsibilities according to the region assigned, if applicable. The users are mapped to the maintenance task/activity according to the roles and responsibilities assigned for the building and region.

User	E-mail	Company/Organization	Title	Department	Roles	Administrator
	td9076@student.uni-lj.si		Maintenance Manager	O&M	Maintenance contractor	
Aleš Korbar	ak@dalux.com	Dalux			HelpDesk and Callcenter	✓
Dalux Support	support@dalux.com	Dalux			HelpDesk and Callcenter	✓
Dorji	dorji805tshewang@gmail.c...		Analyst	Engineering	Maintenance personal	✓
Sempa Dorjee	sempadorjee@gmail.com	ABC	Maintenance	O&M	Maintenance contractor, Maintenance perso...	✓
Tashi	tdor606@aucklanduni.ac.nz	BPC	Operator	Construction	Operation personnel	
Tomo CEROVSEK	tomo.cerovsek@fgg.uni-lj.si	University of Ljubljana		Professor	Portfolio manager	✓
Tshewang Dorji	tshewangdorji@dhi.bt	DHI	Student	BIM A+	Admin - by Tomo, HelpDesk and Callcenter, P...	✓

Figure 48. User roles and responsibilities in Dalux user modules (Dalux FM)

3. O&M modules

The O&M modules define the user maintenance requirements such as work order templates, work order types, checklists, priorities of activities, QR scanning of assets, service agreement with external stakeholders, and invoice and budget allocation. This O&M module binds all the user-defined entities to process the maintenance activity. The historical record of each maintenance task/activity is collected and archived.

4. Asset Classifications & Properties

The ventilation system's assets are classified according to the classification system adopted. All the ventilation components are mapped and linked to the system, space, and building. critical properties of each system and component are user defined within the classification system. The process of ontologies mapping is integrated within the Dalux FM system.

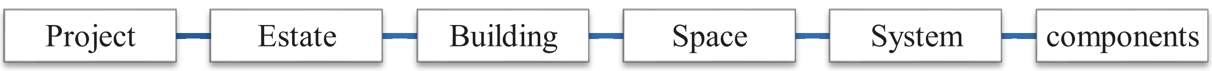


Figure 49. Ontologies mapping

The next phase is to set up the classifications and properties of all the ventilation systems of the building. Since the scope of maintenance for this case study is only confined to the ventilation system, the major components are mapped to the system, space, and building project. The asset in the Dalux FM are installations, building parts, equipment, etc. The asset is used to create user-defined metadata, collecting data, warranties, QR support, maintenance history and planning, placement, and analytics. All the assets considered for maintenance activity are classified as per the classifications system (Uniclass/uni-format/master-format) and their critical properties are defined (heat, vibrations, speed, flow, temperatures, pressure, etc). The classifications and properties of the ventilation system are defined accordingly.

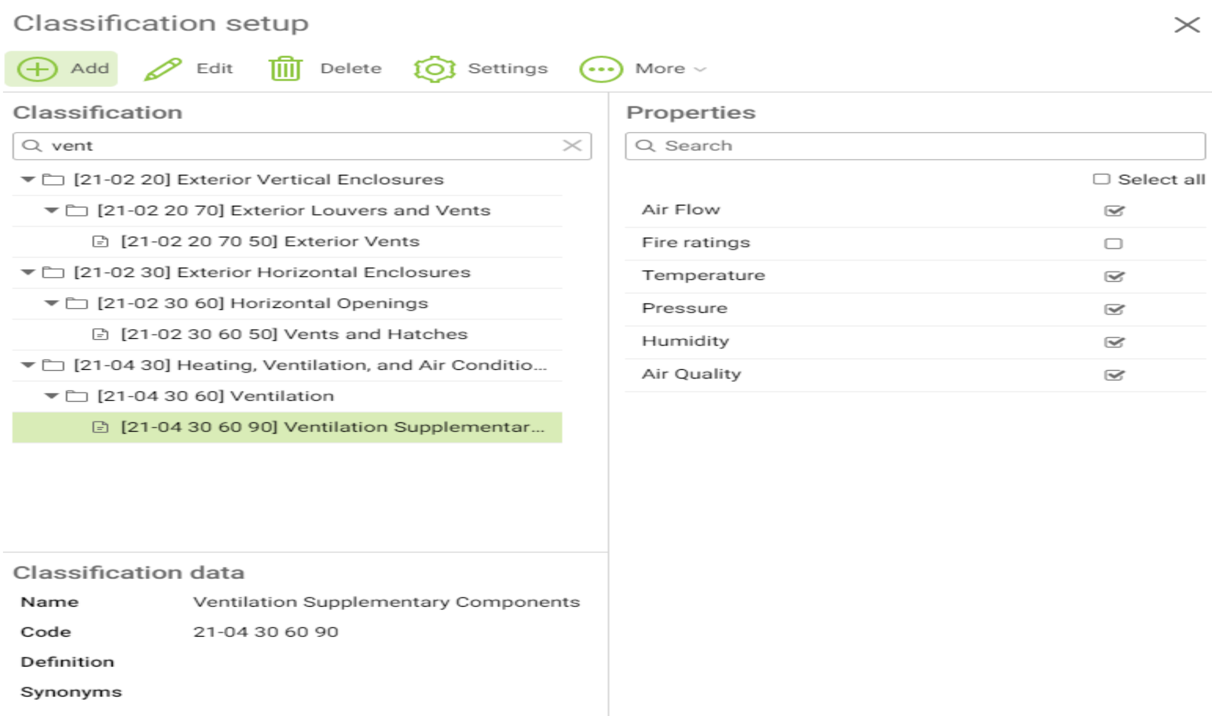


Figure 50. Classification and properties definition for a ventilation system (Dalux FM)

5. BIM & Documentations

BIM & documentation modules allow the linking of ventilation system components/products with the maintenance process defined for the building. Using the BIM link or point cloud, each asset is classified according to the classification system adopted. The assets can be captured from 3D models or the point cloud data source. are filtered from 3D models for easy asset tracking and visualization during the maintenance task/activity.

BIM Link

Add Edit Remove

BIM link name	Classification
M_Exhaust Grille	21-04 30 60 90 Ventilation Supplementary Compo
M_Extract Diffuser_USR	21-04 30 60 90 Ventilation Supplementary Compo
M_Supply Diffuser_TKB-100(R1)	21-04 30 60 90 Ventilation Supplementary Compo
M_Supply Grille_IQFC-240-1-X+IQAZ	21-04 30 60 90 Ventilation Supplementary Compo
M_Supply Grille_RON 1-100	21-04 30 60 90 Ventilation Supplementary Compo
Round Duct_Exhaust Air_125mm dia	21-04 30 60 90 Ventilation Supplementary Compo
Round duct_Exhaust Air_250 mm Dia	21-04 30 60 90 Ventilation Supplementary Compo
Round Duct_Exhaust Air_50mm dia	21-04 30 60 90 Ventilation Supplementary Compo
Round Duct_Supply Air_125mm dia	21-04 30 60 90 Ventilation Supplementary Compo
Round Duct_Supply Air_250mm dia	21-04 30 60 90 Ventilation Supplementary Compo

Figure 51. Asset registration via the BIM link- (Dalux FM)

6. Helpdesk and Work order Modules

The helpdesk module supports reporting, generating, and assigning tickets and work orders to the internal team or external stakeholders. This module binds all the maintenance process requirements including people, process, GIS location, and asset models. Various types of maintenance (preventative, replacement, mitigating, or service order) are carried out for the ventilation system. The general maintenance process flow diagram of this module is illustrated below;

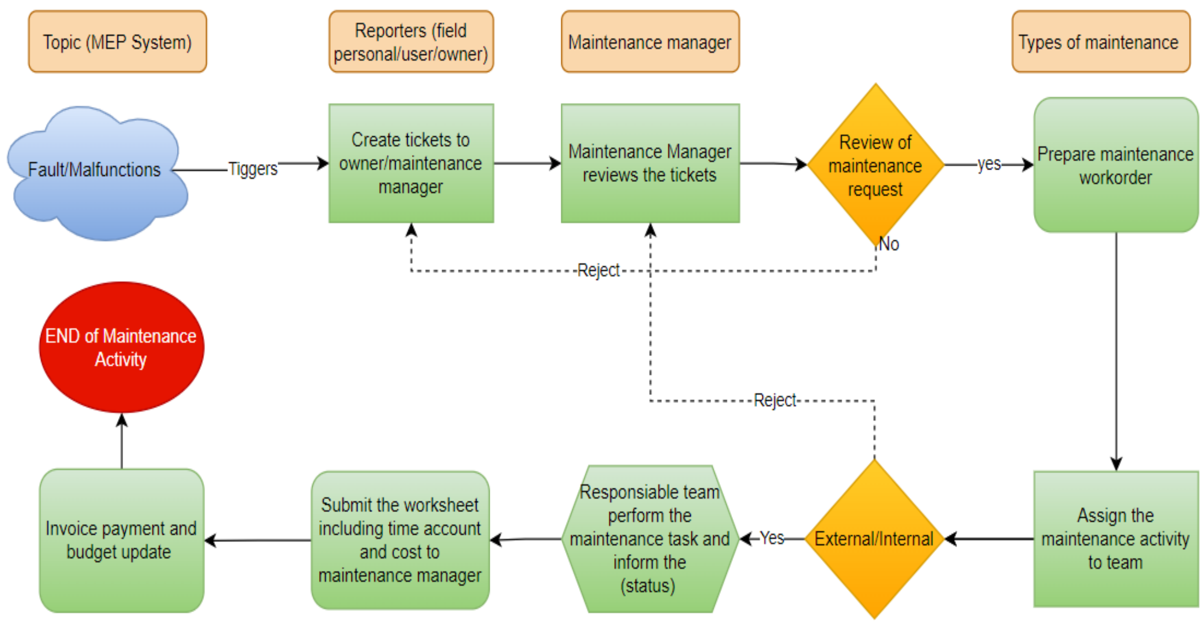


Figure 52. Flow diagram of the work order process (Own Work)

The reporters are the person identified and responsible for different maintenance areas or in some cases building occupants/dwellers initiating the tickets. They tiggers the first instances of requirements for maintenance work in the form of tickets which are systematically forwarded to the maintenance/estate manager. Depending on the nature of the maintenance work requested via the ticket received, the maintenance manager reviews the severity of the maintenance task required and decides whether to seek additional information from the reporters, reject the maintenance request or create formal work orders. The work order is prepared in the work order template designed for the maintenance of that particular asset. The work order consists of descriptions, site images, locations, deadline, cost, responsible team members or service contractors assigned to responsible individuals from the team, and types of maintenance work and priority assigned.

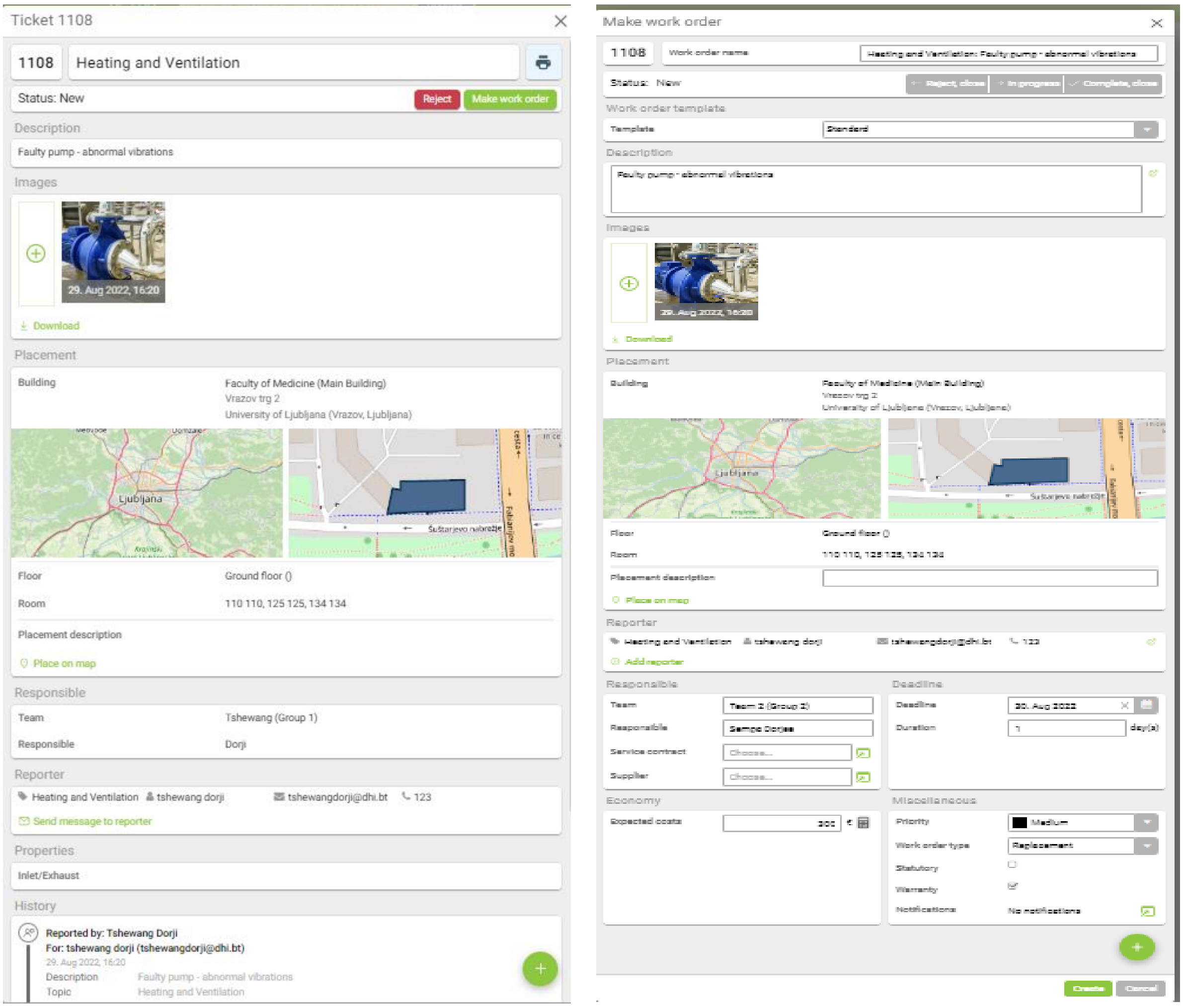


Figure 53. Workorder & tickets

The responsible person assigned to perform the maintenance task can seek additional information or perform the work order issued to him. The responsible person updates the progress or completes the task and status back to the reporter and manager who assigned the job. The time taken for maintenance is recorded and informed to the reporter and maintenance manager for invoice and payment bookings. For maintenance work outsourced to an external service contractor, the maintenance process remains the same. All the information is communicated to the team members and external contractors through email messaging. The task can be updated anywhere through a mobile device or web login. The budget and account module is also integrated with maintenance tasks to perform automatic invoice processing and budget update.

The process of initiating, generating, and assigning recurring maintenance work orders is similar to the normal work order process. The maintenance task is assigned to the internal team or external suppliers/vendors for the scheduled period as per the service contract agreement. The option to connect with the supplier portal is available on this platform. Invoice payment and budget booking for the periodic maintenance are auto-generated based on periodic maintenance sheets submitted by team members or external vendors.

7. Notification modules

This module helps to push the notifications to the internal team members and external vendors such as manufacturers, and suppliers associated with the maintenance project through a service contract. The ticket, work order, recurring work order, and supplier associated with the operation and maintenance task are informed through push email, messages, call and other communication portal established. The sample email message pushed by Dalux FM is shown;

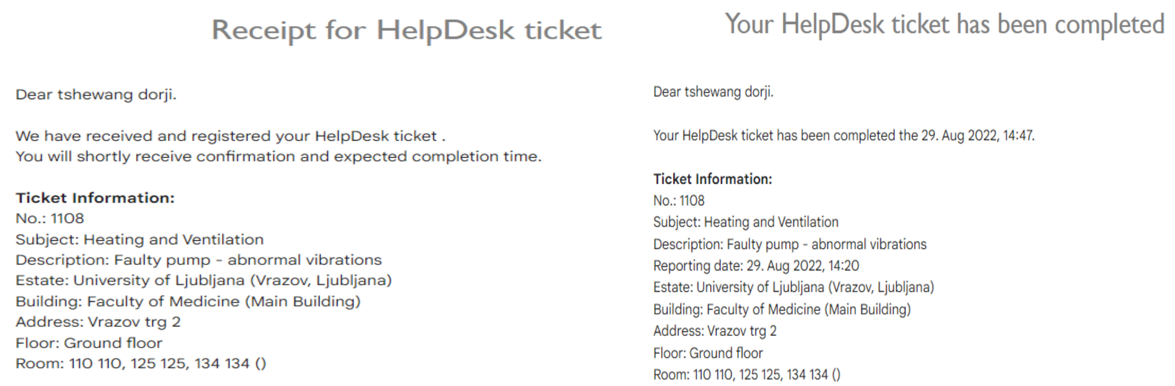


Figure 54.Push message generated in Dalux FM

8. Userfield

This module supports the definition of miscellaneous user fields necessary for operation and maintenance activity. The user field allows the creation of any additional fields with the desired value which can be text, integers, URL links, options for the project, buildings, lots, area, company, contract, ticket, work orders, products, rooms, documents, etc.

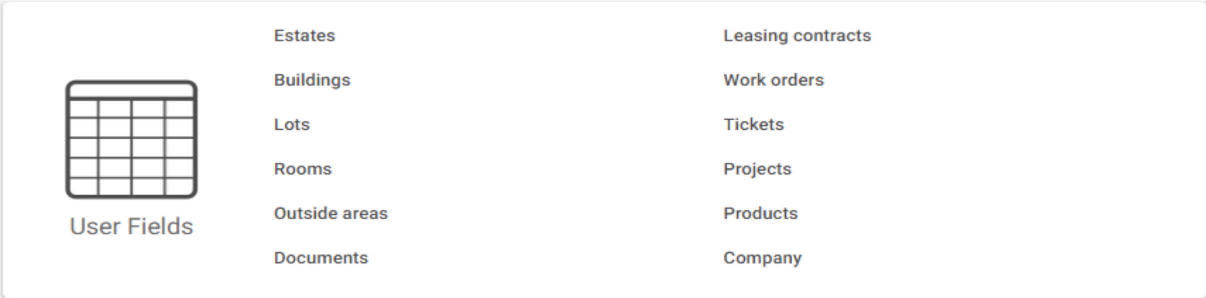


Figure 55. User fields (Dalux FM)

9. Budget

This module allows keeping track of invoices payments and budgets by linking the work orders and recurring work orders completion with the budget plan defined within the system. The budget is allocated for each maintenance type or building. The work orders are assigned with a predisposed budget and the remaining budget available is indicated in budget modules. After completion of the maintenance task, the economy is closed and the actual invoice amount is charged to the budget. The recurring work orders book the budget automatically on the scheduled period and update the real-time budget status. Finally, the project plans support budgeting for additional work required during the O&M phase for renewal or refurbishment projects.

10. Integrations

Azure Active Directory (Azure AD), part of Microsoft Entra, is an enterprise identity service that provides single sign-on, multifactor authentication, and conditional access to guard against 99.9 percent of cybersecurity attacks (www.azure.microsoft.com 12/09/2022). This has the following functions; Single sign-on simplifies access to your apps from anywhere; Conditional access and multifactor authentication help secure data; A single identity control plane grants full visibility and control of your environment; Governance ensures the right people have access to the right resources, and only when they need it. Application programming interface (API) supports the interface of data from one platform to another application as per requirements for higher DT functions (www.azure.microsoft.com 12/09/2022)

11. Dalux FM Dashboard

This module displays all the critical information on O&M activity. The dashboard displays can be user-defined to push the required information or data from the system using the query and filter system. The dashboard provides summarized information on all the O&M activities undertaken.

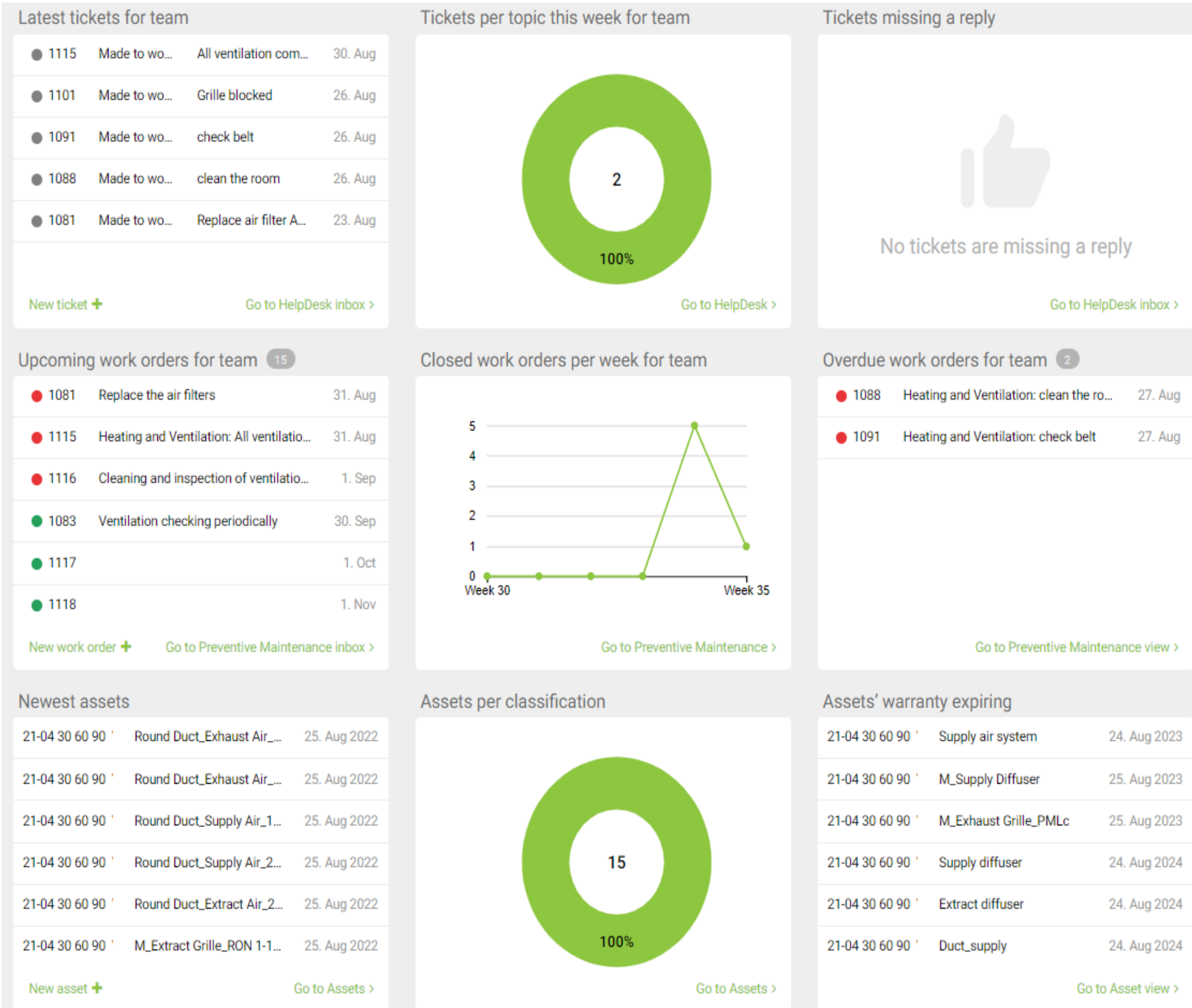


Figure 56.Dashboard modules (Dalux FM)

4.3.2 Result Discussion

As the objective of this study is to demonstrate the "Practical application of a framework for digital twin during the O&M phase of the building". The state-of-the-art digital twin framework applied for O&M of various building assets is examined in the literature review. The frameworks were closely evaluated to identify the DT requirements; architecture layers, enabling technologies, and value generated for the O&M phase. Additionally, the practical implementation of the DT for the O&M phase was conducted using the Dalux FM software to understand the integrations of O&M activity with the DT architecture. Another objective was also to identify the gap and limitations of DT capabilities for O&M functions using the Dalux FM proprietary software and propose the comprehensive DT framework required for the O&M of the Building system. The result of practical application is evaluated against each DT architecture layer and the framework for practical application of DT for the O&M phase is proposed.

DT Architecture Layers

This DT framework architecture layer comprises five components applied in sequence respectively, preparation layer, data acquisition layer, data processing & transmission layer, digital modeling, integration & visualization layer, and application layer

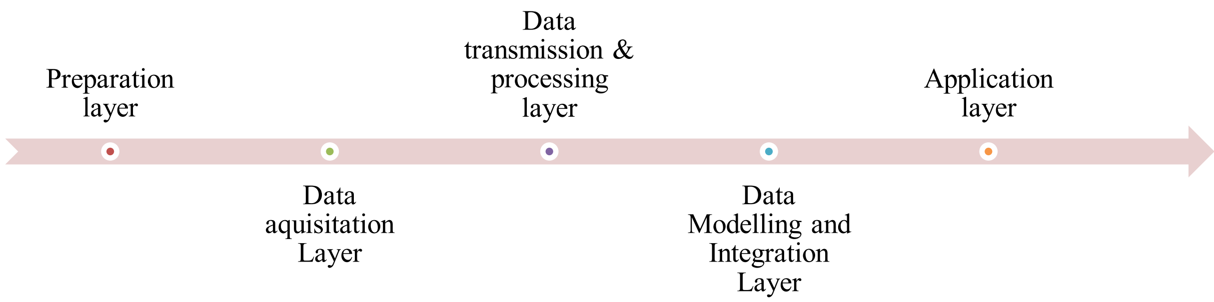


Figure 57. Progressive DT layers

DT Preparation layer – This is the first layer to fulfill the prerequisite for DT implementation. This layer is the most important step to define the scope of successive layers based on the objectives of DT. As per Gemini principles, all DT should be driven by purpose in mind, This purpose informs the preparation of prerequisites for the DT. The preparation layers review the asset management strategy of the organization to select the best strategy required for the digitalization of assets to improve the performance gap. Since the value of DT lies in the quality of data, the process of the information management framework plays a crucial role in ensuring the flow of data in the O&M phase. The ISO 19650 (Delivery and operation) standards define the data exchange protocols. For the BIM model to be used for the DT platform, the level of information need (LOIN) for each model (architectural, structural, MEP) is defined in terms of geometric, alphanumeric, and documentation as required for the DT intent. LOD of all the BIM components required for the operation and maintenance are prepared accordingly.

Data acquisition layer – This layer is the foundational step of DT, The sources for relevant data required for DT are identified in this domain. This layer prepares the capturing of digital parameters from the physical asset identified for the DT. The building operation and maintenance data are captured and stored in a heterogenous manner in an existing system such as BMS, CMMS, and AMS. The goal of DT implementation will determine which data to acquire from the heterogeneous sources. The BIM models for existing buildings are captured by using technologies such as laser scanning, 3D point cloud, and photogrammetry. This layer support data capture and upload from relevant building asset using advanced techniques such as sensors, QR code, RFID, and imaging processing from the distributed asset through IoT-enabled wireless communication, Wifi, and mobile services. Some O&M data are uploaded through the user feedback platform. Other sources of public data that include weather and climate data are acquired as per requirements.

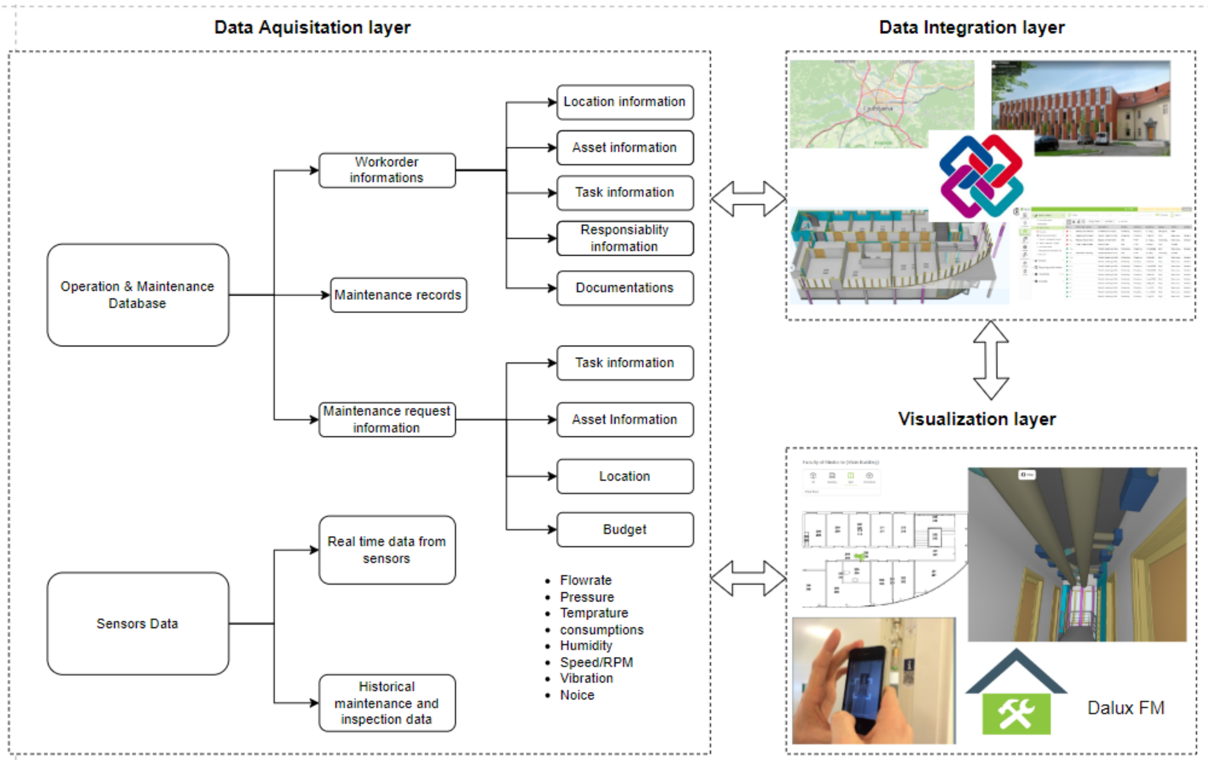
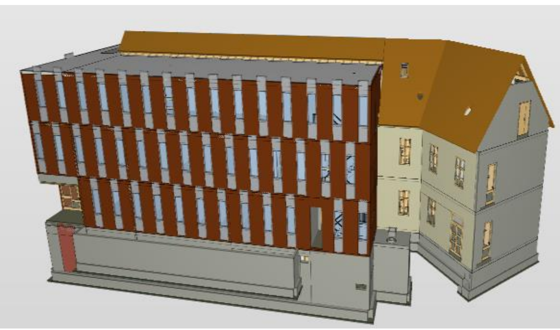


Figure 58. Dalux FM O&M Integrations (Own work)

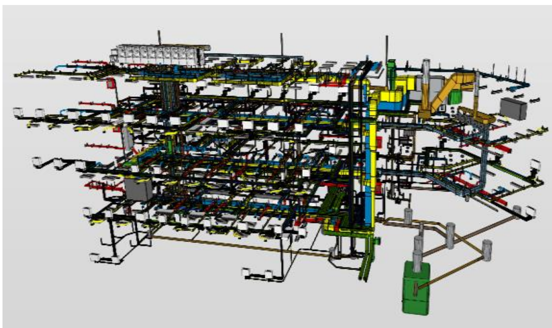
Data processing & transmission layer – This domain layer transform and transmit the data to the upper layers. A significant volume of data is collected from physical assets and the environment during the O&M process. Since this data comes in various forms (structured & unstructured), It requires transforming the data to a useful and readable format by preprocessing the data or undergoing the clean-transform-store process. The O&M data generated every day from the sensors and O&M activity are in massive quantity. Therefore, big data management services are required for transforming, processing, and storing those data. This data management cloud service is currently provided by Amazon Web

Services (AWS), Google Cloud, and Microsoft Azure. For the transmission of data from sensors attached to the physical asset of the building, various communication technologies are available such as LAN (Local area network), WAN (Wide area network), and 5G. Extract-Transform-Load (ETL) technologies support the extraction of data from correct sources (physical assets), transform the data into a common and readable format using business rules, and load the data into a warehouse for use in the upper layer of DT.

Data/model integration & visualization layer – This layer is the most complex layer and is the kernel of the DT architecture. This layer performs multiple critical functions such as data and model storing, analyzing, integrating, processing, and AI-supported decision-making functions, etc (Qiuchen Lu et al., 2019). The dynamic data analysis happens in real-time and processes the up-to-date as-is conditions of the building asset including work order, current status, and historical information of maintenance performed and future prediction of the asset. The integration of AI, ML, data analysis, and simulation engines perform intelligent functions such as space & energy optimization, and O&M optimization. This layer integrates external data of BIM models at a semantic level using IFC schema which supports the representation of components, properties, and attributes and establishes a relationship with other data sources using appropriate application program interfaces (API) such as Autodeskforge. For visualization of model and data, dashboard displays of the model in a local computer or advanced AR/VR tools are used for the detection of assets and faults associated with the asset and resources required for maintenance.



Digital Twin model– Building model



Digital Twin model– MEP system

Physical Model

Sensor – Asset Information

Figure 59. Physical & Digital Models (Own work)

Application layer - This is the final layer of the DT framework and provides the user with interactive functions. This layer displays the various functions designed for asset management which include preventative predictive maintenance tasks, work order management, anomaly detections, and other FM functions such as energy and space management.

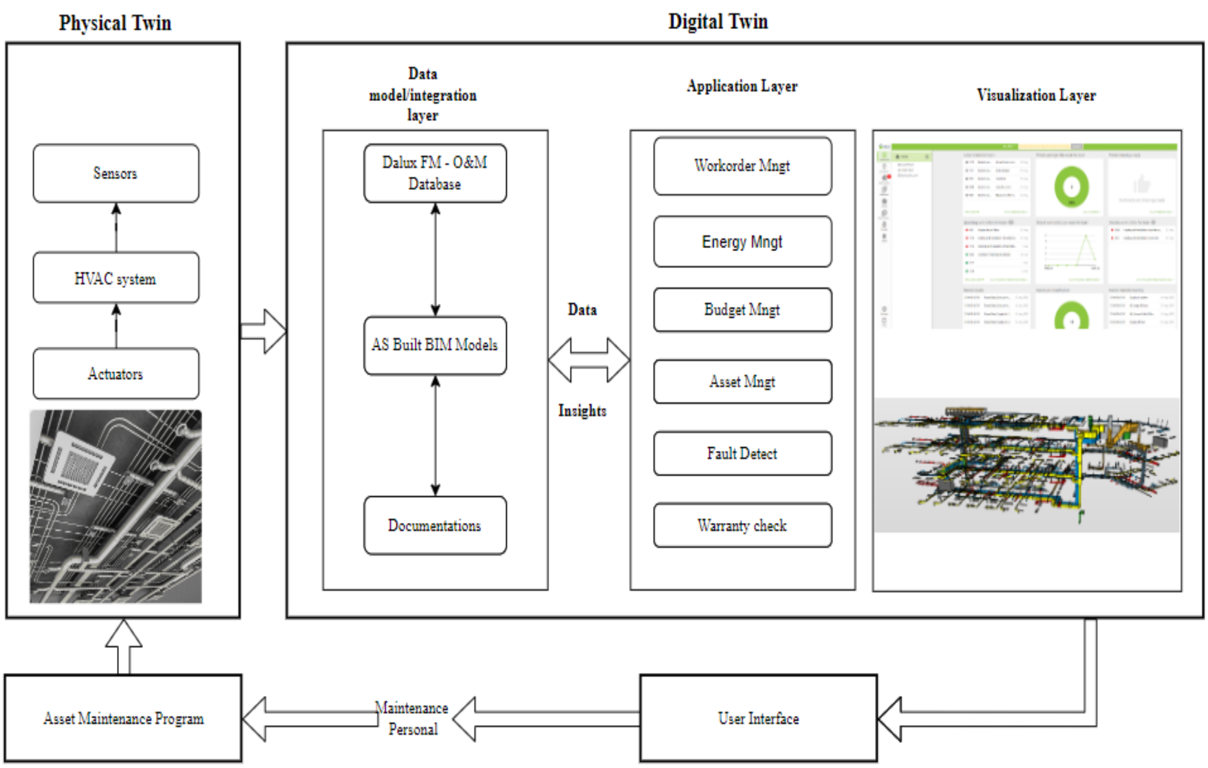


Figure 60. .DT framework for O&M of HVAC system

4.3.3 Proposed DT Framework for O&M Phase

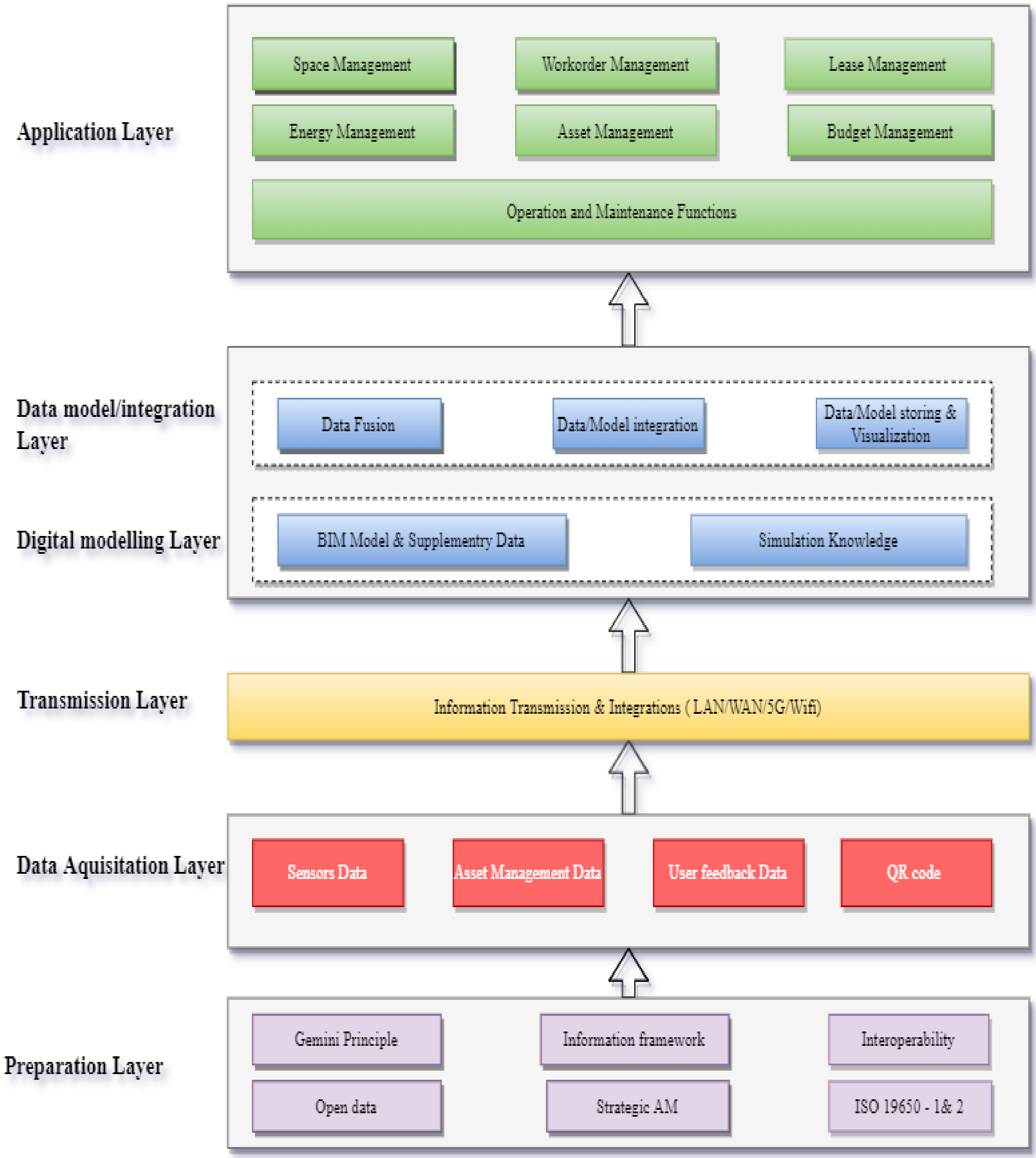


Figure 61. Proposed DT framework for O&M phase

5 DT BENEFITS FOR THE O&M PHASE

Successful implementation of the digital twin has the potential of unlocking economic, social, environmental, and business value in the built asset industry (Quaye, G.M, 2021). The general benefits of DT application in the O&M phase as per (Autodesk, 2021) are summarised below;

Optimized performance
Actionable insights, simulations, and a connected view of all online and offline data enable quick and better decisions to optimize performance and efficiency.

Full view of all data
Eliminate data silos and unlock value across a project's lifecycle with all historical data and real-time data in one place.

Smarter predictions
With real-time sensor data and predictive recommendations through machine learning and artificial intelligence, maintenance and operations are significantly improved.

Faster results
Creating digital twins of complex assets, factories, and processes exponentially improve the value from operations, reduce development work, and increase time to market.

Some of the real values that can be derived from the implementation of this DT framework for the O&M phase are;

- Reduction in faults and requested repairs through timely maintenance activities
- Advance detection of anomalies through analysis of sensor data from critical asset
- Prevention of downtime and catastrophic events using predictive maintenance capabilities
- Budget control, and reduction of O&M costs from prescriptive maintenance strategies
- Can perform preventive actions in the absence of qualified maintenance professionals, - a systematic process with business intelligence.
- Effective environmental & asset monitoring to ensure that the working environment is comfortable.
- Reduction in energy consumption cost – optimization control
- Engaged stakeholders to get valuable feedback on key planning decisions.

6 LIMITATIONS & FUTURE WORK

Significant effort was made on literature analysis and evaluation of the state-of-the-art applications of the digital twin in asset management for the O&M phase. The relevant papers available in the online database are limited and most of the available papers pertain to digital twin applications in the FM-AEC industry in general. These research articles are largely at an early stage of development and the practical deployment of the framework is not addressed.

The contribution of this research work to the existing body of knowledge is limited. The DT framework in this study is already being proposed by the previous researcher. The expert consultations and interviews process could not be conducted to validate the practical usability of the framework. However, the framework proposed is tested by implementing the O&M of the building system using the Dalux FM DT platform. The result indicates the practical implementation of the DT framework for asset management for the O&M phase.

Other limitations in terms of knowledge area include; Lack of standards for creating digital twins in the AEC industry, especially for the O&M phase. However, references are made to digital twin standards and guidelines available for the manufacturing industry and many other relevant BIM-related standards such as PAS 1192, ISO 19650 – 3 for information management in the O&M phase, and ISO 55000 (1&2) for asset management.

Future works proposal includes; an in-depth understanding of asset management and synthesizing the strategic AM principles embedded within the DT architecture rather than just patching the superficial idea of AM to the framework process. For future scalability, DT-enabled asset management at building and infrastructure and ultimately to the city-level need to be explored and developed. The only concern of DT applications is the risk of data privacy and security. Therefore adequate measures must be taken to manage and mitigate the risk. Gemini principle developed by CDBB, SPHERE provides the best practice guidance to create the DT.

7 CONCLUSION

The AEC industry is constantly being challenged by poor asset management practices impacting the productivity of the entire built environment. The demand and expectations to improve the entire value chain of the built environment has become more urgent than ever before, triggered by global interconnected socio-economic-environmental issue. Therefore, AEC practitioners have started applying innovative means to improve asset management strategies by leveraging the power of digital twin concepts and technologies which have become readily available from industry 4.0. The application of digital twin concepts in the AEC sectors has gained significant traction over the last decades due to the benefits it promises.

The AEC industry has already started to implement digital twin concepts and technologies discretely in various phases to improve the performance and productivity of the building asset. The implementation of digital twins enabled the AEC industry to improve its performance of assets throughout the lifecycle which was limited in the BIM-based asset management process. However, digital twins being the newly evolved concept from industry 4.0, there exists much confusion among the AEC practitioners regarding the correct process of implementing digital twins for the operation and maintenance phase. Consequently, due to a lack of clear understanding and guidance documents (standards), the AEC industry is still unable to achieve the full potential and value from the DT adoptions in the operation and maintenance phase of asset management.

This research study's goal was to develop the appropriate level of the framework for the practical implementation of a digital twin for the operation and maintenance phase. The framework development process entails performing a comprehensive literature analysis on the state-of-the-art digital twin implementation in the O&M phase, the thematic applications area and the DT model were evaluated to understand the system architecture and process utilized. The qualitative and quantitative analysis of the selected framework was performed to identify the critical and non-critical components of DT architecture. The limitation and knowledge gaps from the existing frameworks are also identified to propose value addition wherever possible.

The proposed framework is verified at the University of Ljubljana, Faculty of Civil & Geodetic engineering building operation and maintenance project, using ventilation systems as a topic for the case study. Dalux FM is proprietary software used as a digital platform to demonstrate the DT solutions for the O&M phase. The results indicate that The Dalux FM demonstration supported the corroborating and validation of the framework architecture proposed and check the possibility of practical implementation during the O&M phase. The observations made against each layer of the framework proposed with the Dalux FM demonstrations also indicated that most of the architecture layers are fully integrated to perform the DT functions seamlessly.

Although Dalux FM has proven the presence of most of the DT architecture within the system to perform all the DT functions. Some limitations were also observed in the Dalux FM platform, especially for the integration of a higher level of predictive DT solution using machine learning and artificial intelligence are missing. The proposed framework from this study includes all the essential DT architecture layers to create a digital twin solution for the operation and maintenance phase of any asset. The methodology for developing information requirements, operation, and maintenance process flow, and BIM models (Revit/IFC) are also presented as part of the framework proposal.

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