ENHANCING THE IMPLEMENTATION OF DIGITAL TWIN CONCEPT IN BUILDING OPERATION

Master Thesis

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ABSTRACT

Purpose: The Digital Twin (DT) concept is getting more and more attention to be implemented in various industries. This study aims to investigate how the AEC industry could benefit from the implementation of DT. To be more specific, how the operation and maintenance phase could implement the DT concept because with the help of DT data management, decision making, and visualization could be improved during building operation. There would be a possibility to run different simulations. During the operational phase, the outcome of the implementation of DT could be seen as an intelligent platform that could help monitoring, updating, communicating, and integrating Operation and Management issues.

Research Design and Methodology: General literature review was performed to explore the field of building operation and its relation to Building Information Modelling, the historical and theoretical background of the Digital Twin concept, and the level of involvement of the DT concept in the AEC industry. Furthermore, systematic literature review and interviews were conducted and analysed to find ways/methods to enhance the implementation of DT in building operation.

Findings: To enhance the implementation of DT, digitalization in building operation and the components and attributes of DT had been discussed, furthermore the data gathered data from the interviews were supplemented with the systematic literature review to determine what values the DT could provide for building operation. Finally, based on the analyses, a Lean-Agile DT implementation process had been developed to support the enhancement of the DT implementation in building operation.

Key words: Industry 4.0, Digital Twin, AEC industry, Building Operation, Digitalization, Agile development, Systematic Literature Review, Interview, Value Proposition, Implementation

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PREFACE

This master thesis is a research project carried out during the 4th semester of the master's degree in Construction Management and Building Informatics at Aalborg University in Aalborg, Denmark.

This project consists of investigations and outcomes of the research. The process includes explanatory chapters with the historical and theoretical aspect of the Digital Twin concept and the operation and maintenance phase of the building's life cycle. Furthermore, the analyses of the level of digitalization, components of the Digital Twin and the conducted interviews provide an overview on how the implementation of Digital Twin could be enhanced in building operation.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATION

IoT: Internet of Things

AEC industry: Architecture, Engineering and Construction industry

BIM: Building Information Modelling

DT: Digital Twin

CAGR: Compounded Annual Growth Rate

CDBB: Center for Digital Building Britain

bSI: BuildingSMART International

IFC: Industry Foundation Classes

FM: Facility Management

CMMS: Computerized maintenance management systems

EDMS: Electronic document management systems

EMS: Energy Management Systems

BAS: Building Automation Systems

O&M: Operation and Maintenance

FwM: Framework Method

RFID: Radio frequency identification

BMS: Building Management System

FMS: Facility Management System

BEMS: Building Energy Management System

HVAC: heating, ventilation and air conditioning

AHU: Air handling unit

LOD: Level of Development

CAD: computer-aided design

PLM: Product Lifecycle Management

DTP: Digital Twin Prototype

DTI: Digital Twin Instance

DTA: Digital Twin Aggregate

DTE: Digital Twin Environment

PS: Physical Shop Floor

VS: Virtual Shop Floor

SSS: Shop Floor Service System

SDTD: Shop Floor Digital Twin Data

PBO-I: Plan-Build-Operare-Integrate

PBOD: plan-build-operate-decommission

NDTp: National Digital Twin programme

NDT: National Digital Twin

DFTG: Digital Framework Task Group

IMF: Information Management Framework

BDTP: Building Digital Twin Prototype

BDTI: Building Digital Twin Instance

BDTA: Building Digital Twin Aggregate

BDTE: Building Digital Twin Environment

CAFM: computer aided facility management

ML: Machine Learning

AI: Artificial Intelligence

WSN: wireless sensor network

API: Application Programming Interface

ERP: Enterprise resource planning

UI: User Interface

1. INTRODUCTION

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

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

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

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

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

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

1.1. PROBLEM FORMULATION

The main area of our thesis is to improve building operation with the implementation of the Digital Twin Concept.

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

In order to the AEC industry to fully benefit from the digitization drive as a result of the fourth industrial revolution, it is suggested by (Brilakis, et al., 2019) to embrace or apply the concept of Digital Twins throughout the lifecycle of the built environment. In this paper, the focus is on the operation and maintenance phase of the building's life cycle. The Digital Twin concept would involve integrating operational building data from sensors and other sources while ensuring data integrity and interoperability, including analyzing and simulating the building's operation during its lifecycle. With the help of DT, data management, decision making, and visualization could be improved during building operation, and there would be a possibility to run different simulations. During the operational phase, the outcome of the implementation of DT could be seen as an intelligent platform that could help monitoring, updating, communicating and integrating Operation and Management issues.

The goal of the thesis to investigate the current status of development and implementation of the Digital Building Twin in the AEC industry and describe how digital building twins can add value during the operational phase of the building lifecycle by proposing an implementation process diagram on how the concept can be implemented. The above-introduced problems lead to the main research question of this paper:

How to enhance the implementation of the Digital Twin concept in Building Operation?

Followed by sub-questions to narrow down our focus:

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

1.2. RESEARCH OBJECTIVES

The research objectives of this thesis are:

- The Operation and Maintenance of the building’s life cycle, focusing on the essential function of building operation, the different building operation systems that are implemented in the Operation and Maintenance phase, and the level of digitalization in building operation.

- Digital Twin Concept, furthermore, exploring its background and the connection with the AEC industry and looking into how DT is defined by the stakeholders of the AEC industry and finding real-life examples of DT implementation to define the components of DT.

- Looking into in what ways the implementation of the Digital Twin concept could be enhanced for building operation, including what values DT could provide to building operation.

1.3. PROJECT OUTLINE

In this subchapter, the outline of this paper is established; furthermore, the aim of each chapter is described. In *2. Methodology*: The methods used to develop the thesis are outlined to provide a coherent, logical strategy. In *3. Literature Review* the main topics, Building Operation and Digital Twin is explored. Building Operation, where the focus is on the different building operation systems, such as Building Management System, Building Automation System etc. and digitalization in building operation. The next topic is Digital Twin in general and in the AEC industry is defined as well as its relation to BIM is described. In *4. Application of Digital Twin in Building Operation* the systematic literature review and interviews are analyzed to describe the current status of digitalization in building operation, the components and attributes of Digital Twin, and the values that DT could provide to building operation. In *5. DT Implementation Process,* a process is described to implement the DT for building operation, which leads to *6. Discussion and Future Perspective*, where future perspective is outlined and in *7. Conclusion,* the research question and sub-questions are answered.

2. METHODOLOGY

This chapter describes the different methods and chosen approaches to collect data and information relevant to the paper. This paper is based on two primary sources: literature review and interview with different stakeholders of building operation.

2.1. RESEARCH DESIGN

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

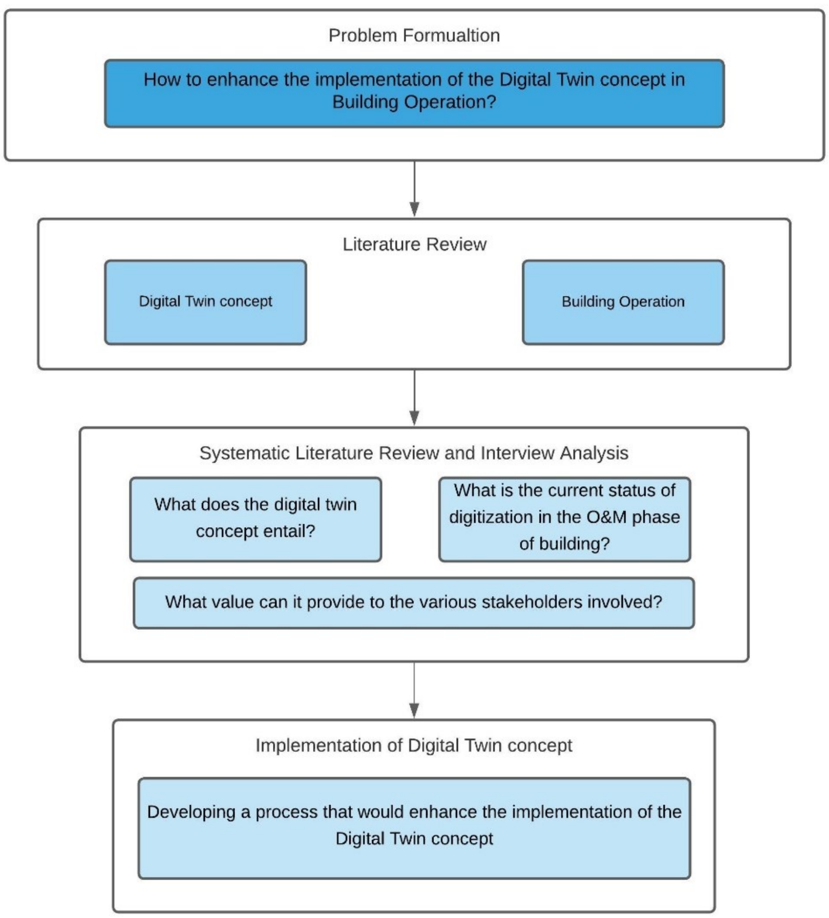

Figure 1: Proposed research design to answer the problem statement

An inductive approach is used to analyse the data received from the interviews and literature review to understand the concept of Digital Twins and the level of implementation of associated technologies and the benefits they provide to the various stakeholders. The research process will be completed by analysing emerging patterns from the data collected through the literature review and interviews. Figure 1 describes the process of research design of this paper.

2.2. DATA COLLECTION

Data collection is executed by performing a systematic literature review and conducting interviews. The chosen methods for both are described in the section.

2.2.1. SYSTEMATIC LITERATURE REVIEW

2.2.1.1. PRISMA

The PRISMA method was adopted because of its ability to help in transparently reporting systematic literature reviews (Moherl, et al., 2011). This method combines an evidence-based set of templates, namely the PRISMA checklist and PRISMA flow diagram. The checklist is broken down into seven different topics with sufficient checklist elements. The goal of the checklist is to help the authors towards critical analysis of selected research papers. As the next step, to choose the essential research papers, the PRISMA flow diagram is intended to be used. The diagram consists of four stages:

- **Identification:** in this step, the relevant databases for research are selected, and keywords for the research are defined. In order to be able to continue, the duplicates found in different databases are excluded.

- **Screening:** in this step, the research papers are assessed depending on the title and, later on, the abstract and the introduction and conclusion.

- **Eligibility:** In this step, the research papers are assessed by full text.

- **Included studies:** in this step, the authors decide, based on the assessment, how many of the research papers will be included in the literature review.

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

2.2.1.2. SNOWBALLING

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

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

2.2.2. SEMI-STRUCTURED INTERVIEW

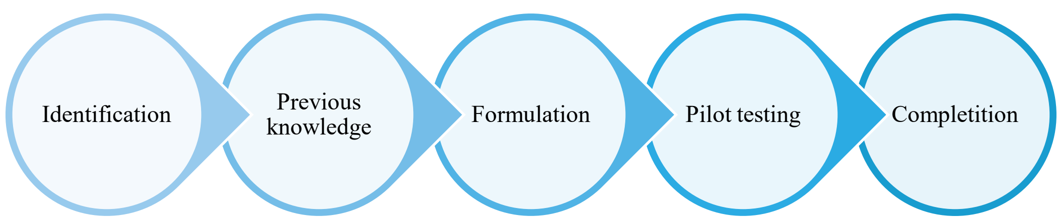

Figure 2: Semi-structured interview guide based on (Kallio, et al., 2016)

The second part of collecting data in this paper was executed by conducting semi-structured interviews with the relevant stakeholders within the scope of the building's life cycle to better understand the stakeholders' point of view regarding the researched problem.

The interviews have been executed as semi-structured interviews based on Figure 2, which visualizes a framework for a qualitative semi-structured interview guide (Kallio, et al., 2016). This method is combining both structured and unstructured interview styles in order to benefit from both as well as the interviewers have the possibility to improvise follow-up questions based on the interviewees' answers. (Kallio, et al., 2016) described a framework that consists of five steps. First, the necessity of the interview is identified (Identification); afterwards, Previous knowledge, such as literature review, is used for the Formulation of the semi-structured interview guide, meaning interview questions are defined based on previous knowledge. As a next step, the interview guide goes through Pilot testing, where the goal is to validate the relevance of the formulated questions and determine the need for reformulating the questions. The last step is the Completion of the interview guide, which is a clear and logical guide for data collection.

2.3. DATA ANALYSIS

The Framework Method (FwM) is chosen in this paper to analyse the qualitative data provided by the interviews. The FwM is used for qualitative content analysis, where common factors and differences are identified in qualitative data; for instance, in interviews, to gather descriptive and explanatory outcomes due to themes, i.e., group of data. (Gale, et al., 2013)

Its main characteristic is the matrix output: rows, i.e., cases such as interviews, columns, i.e., codes and cells of data, contributing to be able to structure and analyze collected data from the interviews systematically. The fundamentals of the qualitative analysis are comparing and contrasting the data. The capacity of comparing data across cases and/or amongst individual cases is part of the process and structure of the FwM. The FwM presents stringent steps to lead towards eminently structured and summarized data. Though the different interviewees might have different points of view or experiences regarding the topic, it is possible to compare and contrast. (Gale, et al., 2013)

FwM is a flexible tool that can be integrated with several qualitative approaches where the goal is to create themes. Developing the themes is a relatively often seen element of qualitative data analysis, including a systematic investigation to find patterns to develop complete descriptions that draw attention to the problem under research. (Gale, et al., 2013)

In this paper, a combined deductive and inductive approach is appropriate as the project has explicit problems to research, nevertheless planning to leave space to explore unforeseen views of the interviewees' experience. For instance, new insights from the interviewees might propose confidential enquiry, where close analysis could expose divergence in the data; thus, it requires follow up exploration. (Gale, et al., 2013)

The Framework Method has seven steps described by (Gale, et al., 2013):

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

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

3. **Coding:** During this step, the transcript is read line by line and labelled with paraphrases that explain the paragraph's interpretation, referring to its importance. The goal of coding is to classify the data so systematic comparison can occur with other data sets, i.e. other interviews.

4. **Developing a working analytical framework:** In this step, the codes from the previous step are categorized into clearly defined themes, which develops a working analytical framework.

5. **Applying the analytical framework:** the previously defined themes are applied by categorizing the data from the transcripts.

6. **Charting data into the framework matrix:** Qualitative data are extensive. As a result, it needs to be summarized and reduced so the analysis process will easier. In this step, the data are charted into a matrix. In the matrix, the data are charted by outlining the data by the different categories from the transcripts.

7. **Interpreting the data:** In the last step of the FwM, the data indexed by the defined themes are interpreted for the defined purpose of the interviews.

2.4. FINDINGS OF THE ANALYSES

The value proposition canvas is implemented to visualize the findings of the interview analysis, which is supplemented by the systematic literature review. The value proposition canvas is divided into two sections, the customer profile and the value proposition.

The customer profile is further divided into three parts, Jobs or tasks, which is describing the things that the customer's goal to achieve, customer's pain and gain, where pain refers to the things that bother the customer to carry out the tasks or prevents them from being done; and the gains are benefits and goals that the customers would like to achieve. (Osterwalder, et al., 2014)

The value proposition consists of the product, pain relievers and gain creators. The product will give value to the customer; the pain relivers refer to how the product will alleviate the customers' pains, and the gain creators describe how the product will create the customers' gains. (Osterwalder, et al., 2014)

3. LITERATURE REVIEW

In this chapter, the two main topics of this thesis, namely Building Operation (3.1) and the Digital Twin concept (3.2), is explored and the chapter is closed with 3.3 Research Gap.

In subchapter 3.1. the existing knowledge and literature on the Operation and Maintenance phase of the building life cycle are explored where the investigation includes the description of Building Operation in general (3.1.1), the different Building Operation systems (3.1.2) and BIM in Building Operation (3.1.3)

In subchapter 3.2. the existing knowledge and literature on Digital Twin is explored, the investigation includes the description of the Historical Overview (3.2.1), the Theoretical Aspect of Digital Twin concept (3.2.2), Digital Twin in the AEC industry (3.2.3) as well as the difference between BIM and DT (3.2.4), lastly describing few use cases that have been done in regards to DT implantation in the AEC industry (3.2.5).

3.1. BUILDING OPERATION

3.1.1. BUILDING OPERATION IN GENERAL

During the operational phase of a building lifecycle, information is generated from a different source and for different purposes. This information is a result of the interaction between human beings and the building and its assets. It is estimated that human beings spend 90% of their time in buildings, which is estimated to be about 50 years. (Lu, et al., 2020) It is therefore essential to ensure optimum comfort and safety of building users during this phase. The responsibility of ensuring the comfort and safety of building users while ensuring the optimum use of the building (Public Buildings) and its assets often fall on the Facility Managers or the building owners.

Advancement and proliferation of software's have enhanced the ways data during the operation phase is accessed and stored, and this sometimes makes it challenging to retrieve required information when these data are stored in different systems. In addition to software, sensors and tags (QR code, RFID) are used to capture real-time data collection by connecting scattered assets into an integrated unit dynamically and intelligently. This is supported by a network technology that provides a remote connection to different data resources and cloud-based services for different platforms. (Lu, et al., 2020) The information needed or generated during the operation and maintenance phase of the building, according to (Lu, et al., 2020), can be classified into geometric and non-geometric. Additionally, (Peng, et al., 2017) summarized the different channels of data in building operation:

1. When a BIM is created, the essential information input occurs manually or acquired from standard component libraries. Day-to-day management records are incorporated by different approaches into existing models. (Liu, et al., 2015)

2. Many entities are converted with the help of algorithms by building management tools, and various frameworks were developed for this purpose. For instance, to store and share knowledge in the management process. (Deshpande, et al., 2014) Most of the algorithms can collect massive data, and other algorithms can convert point cloud data to BIM objects together with semantic information. (Xiong, et al., 2013)

3. The different documents are handed over from the design and/or construction phase to the Operation and Maintenance models. Later on, more documents were added to the building components during day-to-day management. (Peng, et al., 2017)

4. Sensors, both indoor and outdoor, gather a considerable amount of data and direct them to the data repository (Peña, et al., 2016). Location via BIM and RFID technology (Krukowski & Arsenijevic, 2010) are used as data sources (Li & Becerik-Gerber, 2011). These data are usually scattered in the BIM when the different tasks are performed.

3.1.2. BUILDING OPERATION SYSTEMS

During the research, different building operation systems with similar functions and goals were found, these systems are Building Automation System (BAS), Building Energy Management System (BEMS), Building Management System (BMS) and Facility Management System (FMS).

3.1.2.1. BUILDING AUTOMATION SYSTEM AND BUILDING ENERGY MANAGEMENT SYSTEM

Building Automation Systems are used to control the technical facilities, such as heating, air-conditioning and ventilation and supports buildings to be more intelligent using real-time monitoring and control (Redlein, 2020) (Xiao & Fan, 2014). It can also be said to consists of a system installed to control and monitor building services responsible for heating, cooling, ventilation, air conditioning (HVAC), lighting, shading life, safe security, alarm security systems and many more (Domingues, et al., 2016) (Manic, et al., 2016). Depending on the type of building (residential, commercial or public), they usually consist of Building Energy Management Systems, HVAC, lighting, hot water, electrical and IT networks, fire safety systems, vertical transportation (in high rise buildings) and security systems, integrated renewable energy systems, rainwater harvesting, and so on. BEMS controls heating, ventilation and air conditioning, lighting systems. BEMS is a fundamental component of buildings; its task is to minimize energy consumption and maintain the occupants' comfort. (Wijayasekara, et al., 2014)

It acquires data about the building energy performance from its sensors. The data comes from a wide range of sources, including data about occupant's activities in the building, HVAC system, temperature, carbon dioxide, outside air, AHU sensors etc. Typically, some of this data comes in the traditional structured relational data, while others may be semi-structured and others not structured at all. A BAS database stores a considerable amount of various data records, such as temperature, humidity, flow rate, pressure, power, control signals, states of equipment etc. (Xiao & Fan, 2014)

However, during the operation of the building, factors such as rearrangement of indoor spaces, deterioration of thermal characteristics, usage patterns, change in outdoor climate, retrofitting exponentially increase the amount of data generated during the operating life of the building and ultimately affects the capability of the BEMS to successfully integrate and process this data to be able to monitor the energy consumption efficiently. Another problem associated with BAS is that it is usually too complex to be used by non-specialized personnel due to the heterogeneous nature of the data, whether they are end-users or system developers. The heterogeneous nature is partly associated with the lack of commonly agreed field knowledge and functionality gaps, which leads the developers to redefine the basic concepts and develop customized solutions (Domingues, et al., 2016) (Manic, et al., 2016). BEMS systems also do not support the addition and integration of extra sensors due to its legacy formats and the big data and the relatively large volume of data changing at a given time during the operation of a building concerning energy consumption reduces the ability of the BAS to extract relevant and actionable data through its traditional data mining and data algorithm tools (Manic, et al., 2016) (Marinakis, et al., 2020). It is also essential to note the traditionally, 90% of the data generated by smartphones and other connected meters and appliances are never analyzed and acted upon and doing this will help in energy consumption/optimization (Marinakis, et al., 2020).

Nonetheless, the stored data are barely interpreted and used due to inadequate quality of data and the need for effective and proper to be able to analyse vast amounts of data. The modern BAS only supports performing simple data analysis and visualization functions, such as alarm of simple abnormalities, historical data tracking, meaning they cannot systematically analyse massive data. Consequently, there is a need for a more capable and powerful tool that can perform analysis of a large amount of data to gain knowledge to improve building operation. (Xiao & Fan, 2014)

3.1.2.2. BUILDING MANAGEMENT SYSTEM

The typical functions of a BMS are operation scheduling, data collection, trend analysis, DR simulation and activation. The objectives are creating a suitable environment for the building's inhabitants, optimize the use of various equipment, providing a control system that can program time performance, significant reduction of maintenance and optimization costs, monitoring and controlling the operation and maintenance via computer and the probability of statistical reporting of the equipment as well as its performance to improve performance and consumption. (Minoli, et al., 2017) (Mirpadiab & Bagheri, 2016)

A BMS is a comprehensive platform that aims to monitor and control the mechanical and electrical equipment of a building, furthermore, managing loads and improving efficiency; hence, it can decrease the energy demand of the building. A BMS makes connections with control hardware in the different mechanical and electrical systems to monitor and adjust in real-time of energy use. Due to the large footprint of energy consumption, there is a significant market opportunity for technical solutions integrated into BMS that is based on IoT principles. Sensors and user-friendly applications are getting more and more accessible, and these developments are moving the integration of IoT in building applications. IoT concepts will, in addition, standardize, extend and enhance the function and scope of the service. IoT will take BMS capabilities to the next level; for instance, IoT can facilitate intelligent lighting control and optimize the building's HVAC system. BMS allow the building operators to control the energy management; moreover, a

BMS that integrated IoT can be employed to manage functions like surveillance, access and fire detection etc. (Minoli, et al., 2017)

3.1.3. BIM IN BUILDING OPERATION

3.1.3.1. BIM AND BUILDING OPERATION SYSTEMS (BMS AND FMS)

BMS recently prone to aim attention to electrical consumption, so the future BMS (more advanced BMS) is anticipated to focus on all of the energy sources supporting the building, including natural gas, renewable energy as well etc. Sensors/sensor technologies involve demand-controlled ventilation, dedicated outdoor air systems, CO2 sensors, displacement ventilation, energy recovery ventilators, ultraviolet germicidal irradiation and underfloor air distribution. The functions of BMS have developed during recent years to assist these fundamental functions; nevertheless, far-reaching multisystem management that is using one extensive BMS standardization of data flows, data analysis, and actuation continue to be an unreachable goal. (Minoli, et al., 2017)

(Gao & Pishdad-Bozorgi, 2019) organized the O&M activities that could be improved using BIM into six categories; thus, the categories are maintenance and repair, energy management, emergency management, relocation and change management, security, and general FM. Furthermore (Lu, et al., 2020) described that substantial effort was made regarding achieving the development of BIM-enabled asset management from four perspectives, i.e., technology, information and organisation; moreover, they described the limitations well.

- **Technology-wise**, the corresponding limitations are the lack of organized demonstrators and guidelines to select, design, and integrate technology; lack of integration BIM with other systems, and lack of clear and logical plans to update the as-is BIM. (Lu, et al., 2020)

- **Information wise** the corresponding limitations are the lack of predefined strategy to transform various information, lack of clear strategies for saving, exchanging and sharing information, lack of Level of Development (LOD) and information requirement specification for BIM and lack of knowledge on specifying asset management requirements in the earlier design phases of the building's life cycle. (Lu, et al., 2020)

- **Organisation wise** the corresponding limitations are the lack of understanding of the learning processes of BIM in O&M in the early project phase of the building's life cycle, lack of up-to-date management mode, working and service workflows for intelligent BIM-enabled O&M management. (Lu, et al., 2020)

The stakeholders in the building life cycle, such as AEC teams and building owners, are unfamiliar with the application of BIM technologies, protocols and processes in the Operation and Maintenance phase of the life cycle of the building, which enhances technical risks that encompass the scope and obstacle of BIM implementation for FM issue not being defined or understood at the beginning. First, the owner should go through digital FM transformation internally to adjust to the available data and competencies of BIM-enabled FM. Therefore, parallel to handling internal organizational change, owners requesting the handover of FM-ready BIM datasets by the project stakeholders before they complete their own FM integration initiations; thus, without specifying the information requirements accurately resulting in the management of complex issues with great uncertainty. The change of organizational context by the owner and any related project environment will be described by fast technological change and a high level of learning. AEC/FM stakeholders might be required to go beyond their classic responsibilities, roles and scope of work. (Jupp & Awad, 2017)

The implementation of BIM-FM requires both delivering proper as-built datasets when the project is completed, fulfilling the client's requirement for an FM-ready BIM model and O&M documentation, building classification systems and asset hierarchies to correlate with the metadata included in the model. During this, it is vital to consider the current and future information systems, protocols, and processes while simultaneously collaborating with the different stakeholders to provide proper, high-quality data inputs. A consistent and integrated approach to digital FM is essential in attaining the benefits of BIM. Research papers that describe BIM for FM usually concentrate on the delivery phases of the project and neglect the challenges on the client side that are surrounding the constant development and investment needs that BIM-FM approaches demand in building operations. (Jupp & Awad, 2017)

3.1.3.2. BIM PRECONDITIONS FOR BUILDING OPERATION

BIM preconditions are discussed from the Level of Development and nD point of view. Since it based on the discussion of the research on building operation in 3.1.1 and 3.1.2, it can be deduced that defining data and information requirements should be improved, and that could be done by putting more focus on LOD and nD BIM, where LOD is in relation with specifying information requirements and nD BIM is in relation with the purpose of BIM.

3.1.3.2.1. LEVEL OF DEVELOPMENT

The LOD classifications propose that the specifications are more like *"A language by which users can define these requirements for their own firms or projects"* (BIMForum, 2015). The LOD classification is divided into six levels, LOD 100, LOD 200, LOD 300, LOD 350, LOD 400 and LOD 500.

*"**LOD100**: The model element is represented graphically by a symbol or a generic representation. Information specific to the elements, such as costs per square meter can be derived from other model elements.*

***LOD 200**: The model element is represented graphically in the model by a generic element with approximate dimensions, position and orientation.*

***LOD 300**: The model element is represented graphically by a specific object that defines its size, dimension, form, position and orientation.*

***LOD 350**: The model element is represented graphically by a specific object that defines its size, dimension, form, position and orientation as well as its interfaces to other building systems.*

***LOD 400**: The model element is represented graphically by a specific object that defines its size, dimension, form, position and orientation along within formation regarding its production, assembly and installation.*

***LOD 500**: The model element has been validated on the construction site including its size, dimension, form, position and orientation." (Borrmann, et al., 2015)*

The various LODs specify a classification structure for information requirements; according to researchers, the O&M information requirements can be fulfilled with less precision than LOD500 due to the fact that non-geometrical data is more relevant than the high-precision-level of geometric requirements of LOD500. (Mayo & Issa, 2014)

3.1.3.2.2. ND BIM

In the past decades, research has proven that BIM has potential competency for the FM industry by evolving from a conceptual approach to a more practical system. Compare to other technologies, BIM dominates the capabilities for visualization and cooperation. BIM is more valuable in information also; it implicates more dimensions than a single 3D model is created in any CAD software. This concept is called nD BIM are refers to multiple dimensional building information modelling and specifies the complex hierarchies of building information. As the process of the project evolves and becomes automatic, the nD BIM workflows enhance effective and efficient project roles. (GhaffarianHoseini, et al., 2017) As (GhaffarianHoseini, et al., 2017) describes, nD BIM has widely extended capabilities in the various phases of the project, and nD BIM goes from 2D to 7D:

- 2D focuses on drawings. The typical applications are design, plan and shop drawing generation. 2D BIM is implemented in the planning, design and construction phases.

- 3D focuses on entities, and the typical applications are multi-disciplinary coordination, rendering and animation, and digital manufacturing. 3D BIM is implemented in the planning, design, construction, operation and maintenance phases.

- 4D focuses on scheduling, and the typical applications are construction simulations and quality management.

- 5D focuses on estimation, and the typical applications are cost estimation and cash flow analysis. The 5D BIM is implemented during the planning, design, construction and operation phases.

- 6D is focusing on sustainability, and the typical applications are as-built operations and energy consumption analysis. 6D BIM is implemented during the planning, design, construction, operation and maintenance phases.

- 7D focuses on facility management, and the typical applications are building lifecycle assessment and asset life cycle management. The 7D BIM is implemented during construction, operation and maintenance phases.

3.2. DIGITAL TWIN CONCEPT

3.2.1. HISTORICAL OVERVIEW

Figure 3 visualizes the historical development of the Digital Twin concept, which is described in this section.

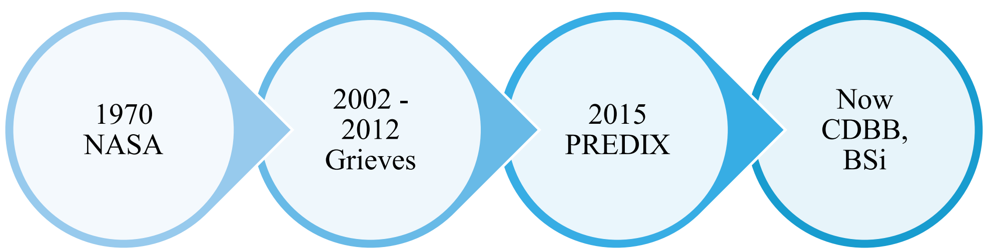

Figure 3: Development of the DT concept from the beginning until now

The concept of Digital Twin can be said to have originated around April 13, 1970, when NASA attempted to land Apollo 13 on the moon. After the astronauts encountered a fault in the oxygen tank mid-air and radio back to the command center, *"HOUSTON WE HAVE A PROBLEM."* The command center undertook a series of simulations and calculations with the help of simulators available at NASA to train the astronauts before their mission.

"The simulators were some of the most complex technology of the entire space program: the only real things in the simulation training were the crew, cockpit, and the mission control consoles, everything else was make-believe created by a bunch of computers, lots of formulas, and skilled technicians." (Gene Kranz, NASA Chief Flight Director for Apollo 13) (Ferguson, 2020)

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

In 2002 Michael Grieves presented the "Conceptual Ideal for PLM" (Figure 4). (Grieves & Vickers, 2016) briefly described the connection between real space, virtual space, and the link for data flow from the real space to the virtual space.

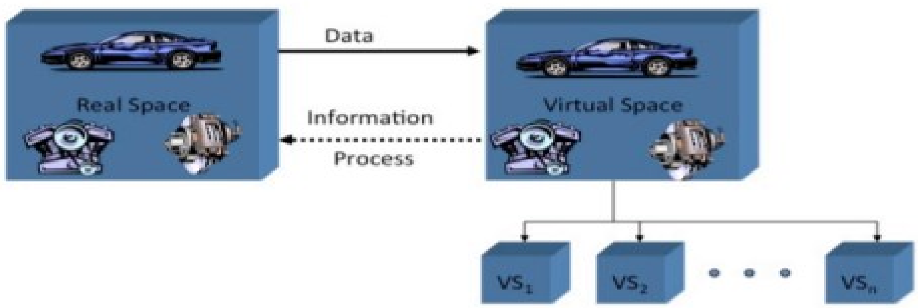

Figure 4: Conceptual Model of PLM By Dr Michael Grieves Source: (Grieves, 2006)

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

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

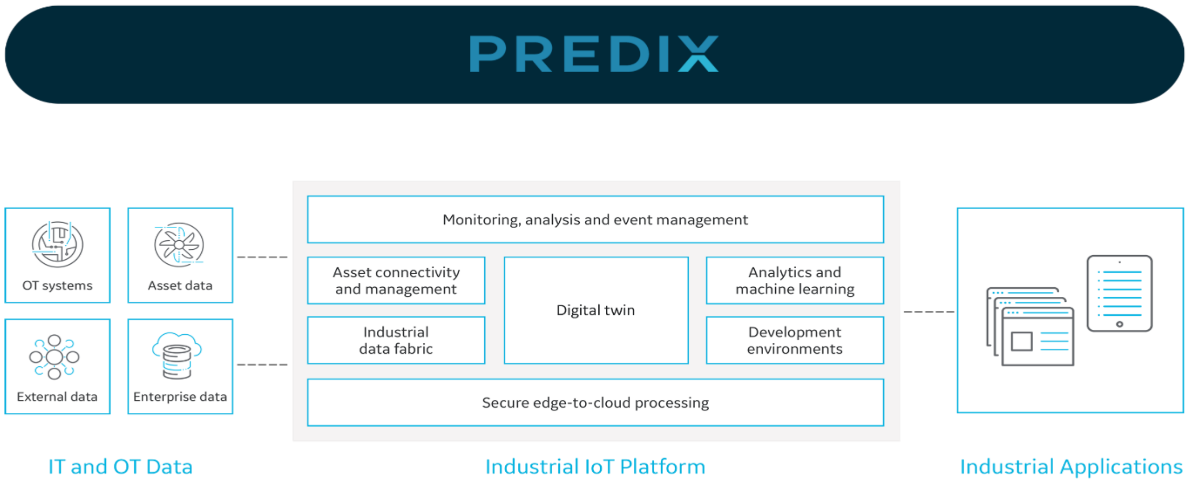

Figure 5: PREDIX (GE, n.d.)

The concept became widely adopted subsequently in various industries, and an example was General Electric (GE) in 2015, built a cloud-hosted Digital Twins of its machines that process information collected from sensors using artificial intelligence, physics-based models and data analytics to manage aeroplane's landing gear, enabling early warnings and failure predictions for several vital components. This Digital Twin, combined with the engine, airframe, and other systems, scale to form a Digital Twin of the entire aircraft (Parris, et al., 2016). Figure 5 briefly explains the components of how GE commercial platform (Predix).

3.2.2. THEORETICAL ASPECT

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

Digital Twins: *"the Digital Twin is a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level. At its optimum, any information that could be obtained from inspecting a physical manufactured product can be obtained from its Digital Twin."* (Grieves & Vickers, 2016)

3.2.2.1. DEFINITIONS OF DT

Table 1 collects the definitions of Digital Twins encountered during the literature review.

Source	Year	Definition
(Glaessgen & Stargel, 2012)	2012	*"The Digital Twin is an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin. The Digital Twin is ultra-realistic and may consider one or more important and interdependent vehicle systems"*
(Lee, et al., 2013)	2013	*"The coupled model is a Digital Twin of the real machine that operates in the cloud platform and simulates the health condition with an integrated knowledge from both data driven analytical algorithms as well as other available physical knowledge."*
(Rosen, et al., 2015)	2015	*"An autonomous system with very realistic models with the current state of processes and their behavior in reaction to their environment in the real world."*
(Schluse, et al., 2018)	2018	*"A virtual replica of a technical asset which contains models of its data (geometry, structure ...), functionality (data processing, behavior, ...) and its communication interface."*
(Canedo, 2016)	2016	*"It's the creating of a digital representation of a real-world object with the focus on the object itself."*
(Schroeder, et al., 2016)	2016	*"A virtual representation of a real product with the product information from beginning of life till disposal in the context of cyber physical systems."*

Table 1: Definition of DT found in different research papers

The common attributes of the DT definitions:

- DT is a virtual replica of the physical product; moreover, it is a highly realistic visualization.

- DT replicate the behaviour of the physical entity as well as its model information and functionality.

- DT implements advanced technologies and sensors to mirror the physical entities operation; also, the data is used to run different simulations.

3.2.2.2. TYPES OF DT

(Grieves & Vickers, 2016) defined several types of Digital Twins, such as Digital Twin Prototype, Digital Twin Instance, Digital Twin Aggregate and Digital Twin Environment, and these different types will be described in this section.

Digital Twin Prototype (DTP): this type of Digital Twin describes the prototypical physical artefact. It contains the informational sets necessary to describe and produce a physical version that duplicates or twins the virtual version. These informational sets include, but are not limited to: Requirements, Fully annotated 3D model, Bill of Materials (with material specifications), Bill of Processes, Bill of Services, and Bill of Disposal. (Grieves & Vickers, 2016)

Digital Twin Instance (DTI): this type of Digital Twin describes a specific corresponding physical product that an individual Digital Twin remains linked to throughout the life of that physical product. Depending on the use cases required for it, this type of Digital Twin may contain, but again is not limited to, the following information sets: (Grieves & Vickers, 2016)

- *"A fully annotated 3D model with Geometric Dimensioning and Tolerancing (GD&T) that describes the geometry of the physical instance and its components,*

- *a Bill of Materials that lists current components and all past components, a Bill of Process that lists the operations that were performed in creating this physical instance, along with the results of any measurements and tests on the instance,*

- *a Service Record describes past services performed and components replaced, and the Operational States captured from actual sensor data, current, past actual, and future predicted."* (Grieves & Vickers, 2016)

Digital Twin Aggregate (DTA): this type of Digital Twins is the aggregation of all the DTIs. Unlike the DTI, the DTA may not be an independent data structure. It may be a computing construct with access to all DTIs and queries them either ad-hoc or proactively. (Grieves & Vickers, 2016)

Digital Twin Environment (DTE): this is an integrated, multi-domain physics application space for operating on Digital Twins for various purposes. (Grieves & Vickers, 2016)

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

3.2.2.3. DT THROUGH THE LIFE CYCLE OF THE PRODUCT

Digital Twin can be implemented throughout the life cycle of the product, during the design, build/manufacture, and operation/maintenance phase, depending on its purpose and (Tao, et al., 2018) described how the Digital Twin concepts could be implemented throughout a product's lifecycle.

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

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

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

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

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

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

3.2.3. DIGITAL TWIN IN THE AEC INDUSTRY

As seen from the previous chapter, the DT concept has been widely adopted in the manufacturing industry (automotive and aerospace sector) to help solve PLM problems, leading to higher productivity and efficiency in that industry. In order to the AEC industry to fully benefit from the digitization drive as a result of the fourth industrial revolution, it has to embrace or apply the concept of Digital Twins throughout the lifecycle of the built environment (Brilakis, et al., 2019). This chapter looks at efforts being made in the AEC industry about the Digital Twin Concept from the perspective of two great organizations BuildingSMART and CDBB, which are focusing on digitalizing and providing open standards in the AEC industry.

3.2.3.1. DEFINITION OF DT IN THE AEC INDUSTRY

Table 2 collects the definitions of DT in the AEC industry that different researchers described.

Source	**Digital Twin definition**
(El Saddik, 2018)	*"Digital Twins will facilitate the means to monitor, understand, and optimize the functions of all physical entities, living as well as non-living, by enabling the seamless transmission of data between the physical and virtual world."*
(Boschert & Rosen, 2016)	*"a comprehensive physical and functional description of a component, product or system together with all available operational data."*
(Nasaruddin, et al., 2018)	*"interaction between the real-world building's indoor environment and a digital yet realistic virtual representation model of building environment, which provides the opportunity on real-time monitoring and data acquisition."*
(Dooley & Camposano, 2020) and (Loscos, et al., 2019)	*"An integrated software solution to manage static and dynamic information of a built asset across its lifecycle phases. It usually provides a realistic digital representation of the physical asset, generated by enriching the geometric or graphical data with support*

	from building automation systems (BAS), sensors, internet of things (IoT) components, and other feedback systems informing about the asset, its occupants, or its environment".
(CDBB, 2018)	*"Digital Twins are realistic digital representations of physical things. They unlock value by enabling improved insights that support better decisions, leading to better outcomes in the physical world."*
(Grieves & Vickers, 2016)	*„The Digital Twin is a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level. At its optimum, any information that could be obtained from inspecting a physical manufactured product can be obtained from its Digital Twin."*

Table 2: Digital Twin definition gathered from the research papers that were used to define the components of DT

The common attributes of the different definitions of the Digital Twin concept are:

- Connecting the physical and virtual entity with operational data.
- The DT functions are to monitor, understand, and optimize the physical entity by analysing the data.
- The DT provides real-time monitoring and visualization.
- DT provides an integrated solution to manage both geometrical and graphical data.

3.2.3.2. BUILDINGSMART AND CDBB PERSPECTIVE

3.2.3.2.1. BUILDINGSMART

BuildingSMART is a worldwide and industrywide go to place to drive digital transformation in the built asset industry.

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

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

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

Figure 6: PBO-I concept of lifecycle Source (Beetz, et al., 2020)

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

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

For the AEC industry, the benefit from implementing the Digital Twin concepts (Beetz, et al., 2020) listed the ways forward as a holistic view of the concepts where all components are part of a more extensive connected system. This could be done by adopting an open and neutral forum where industry stakeholders and experts can discuss and develop a holistic approach to address industry challenges and adopt open standards. This is where BuildingSMART plays a significant role in bringing together industry players and experts.

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

BuildingSMART's approach towards Digital Twins is that the idea of DTs does not necessarily need to be limited to one "model". They are integrating numerous DTs to support the formation of an Ecosystem of DTs. This way, with the Ecosystem of DTs higher value, the broader context of the economic, social and natural environment can be delivered. Nowadays, access to vital information to make the right decision at the right time is a big challenge for several stakeholders of the built asset industry; furthermore, Digital Twins could be the solution to resolve this challenge. An ecosystem of Digital Twins could provide access to integrated data, which is updated regularly, with more visible information unknown at this moment. It integrates static and dynamic data, letting accurate, valuable and up-to-date insights, the basis for well-informed decisions that will contribute to better results and overall better quality of life. (Beetz, et al., 2020)

3.2.3.2.2. CDBB

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

DT 1: A dynamic model of an asset, with the input of current performance data from the physical twin via live data flows from sensors; feedback into the physical twin via real-time control.

DT 2: A static and strategic planning model of a system, with the input of long-term condition data from the physical twin via corporate systems, and loop back the feedback into the physical twin via the capital investment process.

CDBB, in partnership with the University of Cambridge and the Department for Business, Energy and Industrial Strategy, manages the National Digital Twin programme (NDTp) to follow the recommendation of the National Infrastructure Commission's report about Data for the Public Good. NDTp has three objectives that reflect on the importance of data management and make sure that it is beneficial for society. The first objective is to enable a National Digital Twin (NDT), which refers to an ecosystem of Digital Twins, where the several DTs are connected to support better outcomes from the built environment. The second objective is to deliver an Information Management Framework (IMF) to provide secure and flexible data sharing also effective information management. The last objective is to create a Digital Framework Task Group (DFTG), where people from government, academia, and industry come together to share insights, so they pull towards the same direction to facilitate the IMF and, last but not least, to deliver the nation Digital Twin. (CDBB, 2020)

CDBB has an overall vision for Digital Built Britain, expressed in four words; *Design, Built, Operate* and *Integrate*. As BIM stands for Building Information Modelling, it is sort of in *Design* and *Built*. BIM demonstrates how relevant and valuable information is in the delivery process; for example, if the information is lost during the handover, value is also lost. Therefore, it provides a foundation that CDBB can build on. Information can be used to provide more value in the Operation and Maintenance of the asset or system; this is where *Operate* comes into the picture; this is where DT is. Nevertheless, the vision of CDBB goes beyond Operate; the next step is *Integrate,* representing integration across organizational and sector boundaries, which anticipate that *Integrate* is the Connected Digital Twins. (Enzer, 2020)

The next context that CDBB is describing is summarizing how they see infrastructure to put NTD in place. It interprets the scope that they are considering because the NTD is focusing on the built environment instead of focusing on other sectors. **Error! Reference source not found.** visualizes the scope of Systems of Systems. It is based on the five key sectors in the economic infrastructure, to be exact, Transportation, Energy, Telecommunication, Water and Waste. The sectors are a complex interconnected system, which means that they consist of more than one individual system connected and function together for a greater purpose; for instance, in transportation, these systems are rail, road and air. Energy, Water and Waste follow the same principles; furthermore, telecommunication is a complex interconnected system itself considering that it is connected to everything else. Social infrastructure (Hospitals, schools etc.) and Residential, Commercial and Industrial Buildings do not make sense if they are not connected to the five key sectors as it relies on the sectors mentioned above. This defines the System of Systems, which is highly complex; as a matter of fact, it was never designed; society just kept building new assets and connect them into a built environment.

All in all, it is an “essential machine” that is immensely important to society in order to keep going. The context of the NTD is essential, but it lacks tools that help to run it efficiently. (Enzer, 2020)

According to CDBB, implementing a system-based view of the built environment is essential, because today the infrastructure in the construction industry is seen as a series of project, and the infrastructure should be seen as a system and projects as interventions on the system. The system-based view of the built environment has four key perspectives: the system of systems, the system of services, the cyber-physical system, and the sustainable system. So far, the industry is managing the physical asset well; on the contrary, it is having difficulties with the management of the digital assets. The digital asset is genuine; consequently, digital asset management needs improvement. On this note, combining the physical and digital assets indicates intelligent management; moreover, it involves implementing Industry 4.0 thinking, which is the context to DT. (Enzer, 2020)

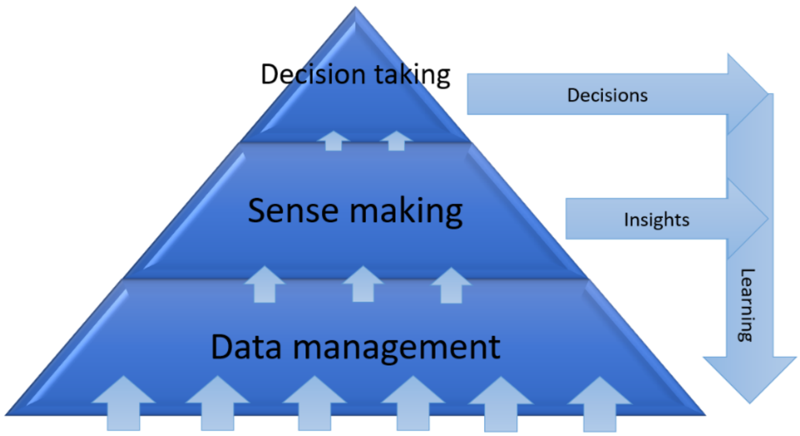

Figure 7: The Information Value Chain (Enzer, 2020)

The key to defining the Digital Twin is the **Information Value Chain** (Figure 7). The Information Value Chain has three level, Data management, Sensemaking and Decision taking. Data management represents the process of making the data usable and structured as it may come from several sources and in different forms. At this level, the data is still just data; therefore, at the next level, sense-making provide the data with meaning and value, which is necessary to generate insights. Furthermore, it creates a chain reaction that can be seen in Figure 8. (Enzer, 2020)

Figure 8: The chain reaction of Sense making

The value chain is necessary to be understood to make the connection from data to the outcomes; thus, improving the data has the actual purpose of improving economic, environmental and social outcomes. The key in all this is that it allows value to be delivered all the decisions; consequently, improved decision making is the focus for DT.

CDBB has been working on a "National Digital Twin" to improve the outcomes from the built environment. The National Digital Twin is imagined to be multiple Digital Twins that are connected; as a result, they compose an ecosystem of Digital Twins. The proposal of the ecosystem approach aims to improve the representation of the nature of the system of systems in the built environment. Apart from the above-mentioned system-based view, NDT will need resilient and secure ways of sharing data between the different "systems" in the ecosystem; this will incorporate data exchange between the digital and physical twins along with the connection between the various Digital Twins. In order to provide secure data sharing that will enable the creation of the

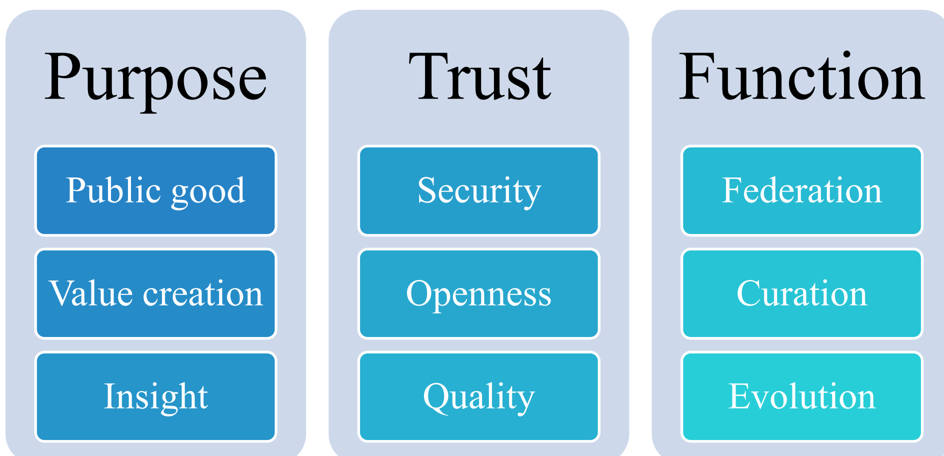

Figure 9: The Gemini Principles (CDBB, 2020)

NDT, CDBB is focusing on the development of an Information Management Framework. The advantages of the CDDB's approach are assumed in four areas: benefits to economy, society, business and environment. (Brilakis, et al., 2019)

CDBB published the Gemini Principles report in 2018 to establish a start to enable adjustment on the approach to managing information in the built environment, so sharing data in the future will be easier by providing common definitions and principles from the outset. The Gemini Principles are efficiently the conscience of IMD and the NDT. In order to make sure that IMF and NDT are for the public good, strong founding values are needed to guide them. (CDBB, 2020) There are nine simple principles, and their significance is challenging, far-reaching, and they are indicated to strengthen the adaptability for development and innovation. The Gemini

Principles set a context within the question that is possible to be identified and addressed rather than answer the key questions about the NDT. Besides, these principles do not try to determine the relative relevance of the individual principles. (CDBB, 2018)

The goal of the nine principles is to ensure that the Digital Twin has a clear purpose, maintain trust and function effectively. The Gemini principles can be seen in Figure 9. Public good, which means that Digital Twins have to be used to provide benefit for the public. Value creation, therefore, that Digital Twins allow better infrastructure performance and improved outcomes for people. Insight to allow better decision making depending on an improved analysis of better data over the built environment. Digital Twins need to enable both securities and be secure themselves; furthermore, they should be as open as possible because the balance between security and openness is fundamental. Digital Twins must be built on data that has sufficient quality for its purpose. Federation refers to that Digital Twins must allow connecting data from various sources and be connectable themselves. Curation means that the data and the Digital Twins are accurately cared for having clear stewardship, governance, and regulation; moreover, the way technology and society evolve Digital Twins should be able to deal with the current evolution. (CDBB, 2020)

3.2.3.3. DIFFERENT TYPES OF DT IN THE AEC INDUSTRY

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

Building Digital Twin Prototype (BDTP): This is used to describe an asset during design and construction containing information that is necessary to describe and produce a physical version that duplicates or twins the virtual one. (Association, 2020) The information includes:

- *"Employer requirements included inside contracts, previous legal and geotechnical information of the land.*
- *An information model in the form of an Object type database, which includes 3D geometric information and materials and elements inventory.*
- *Bill of processes as s comprehensive of past processes and actors based on minutes and confirmed communication.*

- *Bill of Services as the current evolution on the functional characteristics of the asset, starting back from initial employer requirement.*
- *Bill of disposal (e.g. material passports, selected deconstruction techniques)"* (Association, 2020)

Building Digital Twin Instant (BDTI): This refers to a DT linked throughout the life of a specific corresponding physical product, including pairing when the asset starts operation. (Association, 2020) This is similar to As-Built documentation, and it includes but not limited to the following:

- *"A complete information model, including a 3D model with General Dimension and Tolerances, describes the physical instance's geometry and its components.*
- *Bill of Materials that lists current and previous elements and component (architectural, structural, and building services)*
- *Bill of process lists the operations that were performed in creating this physical instance along with the results of any measurement and tests on the instance (e.g. cloud point surveys of inner services, structural load test, etc.)*
- *Service record that describes past services performed and components replaced (major/minor retrofitting and regular upkeeping)*
- *Operational states captured from actual sensor data, current, past actual and future predicted (BMS, SCADA/IOT sensors, Facility Management Servers, simulations)"* (Association, 2020)

Building Digital Twin Aggregate (BDTA): As in the manufacturing sector, this represents the aggregation of multiple DTI's. They do not have an independent data structure but rather a computing construct that provides access to all DTI's, allowing ad-hoc and proactive queries for benchmarking and comparisons. (Association, 2020)

Building Digital Twin Environment (BDTE): This serves two primary purposes, which are Predictive (intimately linked with simulation tools of DTP and DTI), and Interrogative (applying DTI and DTA for in-depth analysis). (Association, 2020)

3.2.3.4. MATURITY LEVELS

It is essential to focus on the purpose of DT and understand the benefits of the different milestones and realize in what ways value grow by maturity. (Evans, et al., 2019) proposed an industry-agnostic maturity spectrum, which identifies various elements and offers a framework for communication of the progress. While the Digital Twin is under development, every element will increase its complexity and connectivity and value. It is fundamental to identify clearly, realize, and justify the increased complexity and connectivity's objective and value that depends on efficient application and management. The physical and digital Twins are connected through a collection of data platforms. This allows data from different asset and document management systems, common data environments etc., to combine in order to support new business scenarios. The key part of the Digital Twin is to be able to run simulations to answer "what if" questions and analyse the data to advise physical asset management. This is an ability that is achievable within all elements of the maturity spectrum. (Evans, et al., 2019)

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

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

Element 1: This element is the usual starting point for a new asset since it is the product of the design process; it can also be updated via reality capture after the construction phase to create an as-built model. The models are object-based, without containing metadata or any BIM information. It converts the point cloud from Element 0 into a 3D model or an object-based 2D map/systems. Today the conversion is a manual process; nevertheless, soon, this process will be semi-automated, including machine learning. At this level, the twin gives significant value through design or asset coordination and optimization. (Evans, et al., 2019)

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

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

Element 4: The condition of the physical asset can be modified through the DT by feeding back the analysis results and updated into the twin. For instance, a physical valve could be manipulated via the initiation of the action from the twin. The integration at this level needs mechanical augmentation and additional sensor of the physical twin. This integration can be applied among the twin and other DTs. For instance, immersive technology can be used to modify the design by a designer; the modification is pushed to the applications that are connected to the twin. The connected applications calculate the impact of the modification and update the geometry and data according to it. These modifications and their impact will reflect in real-time into the twin, and the designer will be able to see it. This integration shows human-to-machine and machine-to-machine interaction with DTs. (Evans, et al., 2019)

Element 5: This level of maturity is simply aspirational at the moment. However, DTs have the potential to learn and evolve to be a source of institutional knowledge and gain valuable experience about the behaviour of the physical twin so that it could be completely autonomous. The full consequence of this level of maturity and the valuable benefits that it will provide are yet to be explored. (Evans, et al., 2019)

3.2.4. THE WAY FROM BUILDING INFORMATION MODELLING TO DIGITAL TWIN

After going through a number of research papers and articles about the Digital Twin Concept and its relation to BIM, different aspects of the two concepts have been found. These aspects are including difference and similarities, as well as discovering a thin line between the BIM and DT.

3.2.4.1. DIFFERENCES AND SIMILARITIES

The Digital Twin concept involves the digital transformation of how an organization operates and involves changing the mindset of the people in an organization to be successful. Building Information Modelling cannot be ignored when digitization in the AEC industry is being discussed. The Digital Twin concept is not a technology but instead relies on a series of other technologies in order to realize its potential. A Building Information model representing a 3D model rich with semantic information serves as a database for all assets and facilitates exchanges of information between stakeholders in a unified and standardized way (Pauwells & Petrova, 2018). BIM is used to avoid failure during the design phase, help communication between the stakeholders, improve efficiency during construction, monitor time and cost of the construction project (Volk, et al., 2014), as well as facility managers, use it for maintenance planning during the building's life cycle (Azhar, et al., 2012). During the operation and maintenance phase, it can also be used as a repository or source of information that supports various activities of existing buildings (Lu, et al., 2020). However, during the O&M phase of a building, the lack of integration and application of BIM, (Lu, et al., 2020) summarised as three main reasons, namely Technology-related issues. Information Related Issues and Organizational Related issues. There is a lack of awareness of the benefits of BIM in the operation and maintenance phases (Shalabi & Turkan, 2017). This partly due to the lack of clear and validated benefits of BIM in facility management practices, lack of integration between BIM and IoT due to problems associated with legacy formats that are not aligned (Boje, et al., 2020) and technological issues in integrating BIM and IoT to monitor assets during operation and maintenance (Becerik-Gerber, et al., 2012). Another reason for this may be partly due to the multifaceted, complex challenges of asset management and the asset management frame's alignment to the BIM information management processes (Lu, et al., 2020).

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

As stated earlier, BIM is likely to reduce the amount of time taken for updating databases during the Operation and Maintenance phases of a built asset by 98% (Lu, et al., 2020). There also exist some similarities in BIM processes and the DT concept. They seek to enhance visibility, align stakeholders, support planning and ultimately enable stakeholders to view the project through its entire life cycle instead of siloed capex investment assets (Bart Brink, 2020). BIM processes and framework establishes a clear project vision and supports business outcomes before actual design starts and construction follows. BIM processes and tools also efficiently manage construction logistics, clash detection, site monitoring, quality management, site monitoring, construction simulation visual communication, and scheduling (Boje, et al., 2020). However, DT is beneficial when there is a need to continuously improve and adapt projects to deliver more excellent value to stakeholders using real-time insight (Bart Brink, 2020). As stated earlier, BIM is likely to reduce the amount of time taken for updating databases during the Operation and Maintenance phases of a built asset by 98% (Lu, et al., 2020) and forms the basis for developing a Digital Twin. Information regarding the project, assets, organization are already agreed on according to ISO 19650, ISO 55000, and ISO 9001 and fits in developing a DT.

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

- *"Clear definitions for the information needed by the project client or asset owner, and for the standards, methods, processes, deadlines and protocols that will govern its production and review.*
- *The quantity and quality of information produced being just sufficient to satisfy the defined information needs, whilst not compromising health and safety or security. Too much information represents wasted effort by the supply chain and too little means clients/owners take uninformed decisions about their projects/assets.*
- *Efficient and effective transfer of information between those involved in each part of the life cycle – particularly within projects and between project delivery and asset operation.*
- *Informed and timely decision making."* (UKBIMAlliance, et al., 2019)

3.2.4.2. EVOLUTION FROM BIM TO DT

(Deng, et al., 2021) came up with five levels of evolution of BIM to DT in the built environment to structure their research (Figure 10). In the case of this thesis, this evolution is used to visualize and describe the difference between BIM and DT.

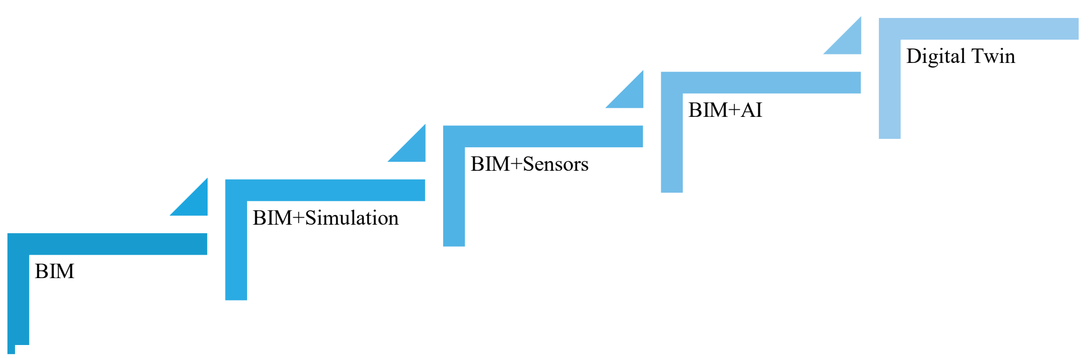

Figure 10: Development from BIM to DT according to (Deng, et al., 2021)

Level 1: At this stage, BIM is used as a tool for static 3D visualization to maintain the needed information to support traditional methods of building design, construction scheduling etc. The use of BIM at Level 1 is intended to ensure improved information sharing between the various stakeholders during the building's life cycle. (Deng, et al., 2021)

Level 2: At this level, the BIM models are starting to be used for analyses and simulations. The BIM models are used as sources of data to conduct analyses of building performance or construction processes. (Deng, et al., 2021)

Level 3: In this level, the building's digital models are integrated with real-time (IoT) sensors to monitor and manage the building environment. After the integration of IoT sensors, real-time data can be collected and visualized in the digital models, which will have the possibility to be used for decision-making or changing strategy throughout any phases of the building's life cycle. (Deng, et al., 2021)

Level 4: At this level, the building environment management and monitoring are enhanced by integrating algorithms for real-time predictions thanks to the data collected via the sensors. Reliable and accurate strategies can be achieved semi-automatically or automatically with convenient decision-making strategies based on real-time prediction. (Deng, et al., 2021)

Level 5: DT includes the capabilities mentioned above of the different levels, such as real-time visualization, real-time prediction that supports decision making; nevertheless, it supports automatic control and feedback of the building as well. In addition to the competencies of Level 1-4, the built environment is facilitated with an intelligent feedback control system that supports taking action automatically based on optimized results. This can be the result of employing advanced technologies, such as AI and/or ML. (Deng, et al., 2021)

3.2.4.3. BIM-ENABLED DT

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

3.2.5. RELATED WORKS

The research by (Stojanovic, et al., 2018) concentrated on designing a data acquisition workflow to collect and develop semantically rich data from 3D point clouds. To capture the current physical state of the built environment, 3D point clouds have the potential to be implemented as the basis for DT representations. As a result, it will support semantically rich models to improve collaboration, decision-making, and forecasting among Facility Management stakeholders. The case study outcomes proved the achievability of generating as-is data representations of indoor environments, including commodity hardware for Facility Management use, especially for space management. The proposal mentioned above has the possibility to improve engagement and decision making for FM professional. Implementing a service-oriented paradigm and with the help of regular mobile devices, the indoor environments can be scanned to be recreated as semantically rich as-is BIM data and as fundamental data for Digital Twins. (Stojanovic, et al., 2018)

(Lu, et al., 2019) developed a case study for developing a dynamic DT at West Cambridge, and the area of the objective was the Institute for Manufacturing. They proposed a hierarchical architecture for a DT-enabled asset management framework. The goal of the proposed dynamic Digital Twin architecture was to integrate composite assets and data sources along with their applications, to support intelligent asset management in order to provide efficient Operation and Maintenance management, furthermore to connect the void between the relationships that humans have with buildings with more visual, intelligent and sustainable channels. (Lu, et al., 2019)

(Lu, et al., 2020) presented the other case study where they were focusing on maximising the value of Digital Twins and presenting how they could aid anomaly detection in daily Operation and Maintenance management. This research presented a DT-based anomaly detection system and an adequate data integration method which is based on extended IFC. The evaluation of the study happened in the Institute for Manufacturing building of the University of Cambridge (West Cambridge site) as well. The goal of the case study was to exemplify how the designed data structure could support the data integration of a dynamic Digital Twin of existing buildings, to help the anomaly detection function furthermore to probe the challenges and opportunities. (Lu, et al., 2020)

The next paper that is worthy of mentioning in this part of the report is written by (Macchi, et al., 2018) where their goal was to research and review the role of Digital Twin in Asset Management, focusing on asset-related decision-making process and understanding of the advantages of the application of DTs in asset lifecycle management. The authors considered Digital Twin modelling as a significant concept to support asset-related decision making. Their final goal was connecting the Digital Twin modelling and Asset Management research areas to assist the adoption of recent technologies and methodologies developed at Key Enabling Technologies, like IoT, Big Data etc., level in the industrial Asset Management context. (Macchi, et al., 2018)

(Xie, et al., 2020) wrote an article that addresses the challenge of automatic temperature anomaly detection and interpretation in building spaces. They explore how Digital Twins and environmental anomaly detection techniques could increase the performance of inspection management with the help of integrating with augmented reality. They presented a visualized inspection system to show the capability for knowledge integration of failed assets and help Facility Management specialists find the main problems of the dominant anomalies. (Xie, et al., 2020)

3.3. RESEARCH GAP

In this section, the research gap of the literature review on building operation that leads towards the implementation of Digital Twin is summarized.

- Lack of commonly agreed field knowledge and functionality gaps.
- The heterogeneous nature of the data is too complex to be used by non-specialized personnel.
- BEMS systems do not support the addition and integration of extra sensors due to their legacy formats.
- The gathered data are never analysed and acted upon.
- The stakeholders in the building life cycle are unfamiliar with the application of BIM technologies, protocols and processes in building operation.
- Interoperability is a great challenge for BAS and IoT technologies.
- It is difficult to identify relevant and abnormal building behaviour and resolve them because of the complexity and the overwhelming amount of the acquired data.
- Current BEMS tools are missing the capability of providing prosecutable information by processing and integrating collected data.

4. APPLICATION OF DIGITAL TWIN IN BUILDING OPERATION

A systematic literature review and semi-structured interview are executed and analysed to find answers for the above-presented problem formulation in this chapter. The systematic literature review is done by implementing the PRISMA method, and the results are summarized in a table. Semi-structured interviews were executed to substantiate the literature review and provide information and knowledge from the relevant stakeholders in building operation.

4.1. SYSTEMATIC LITERATURE REVIEW

After the main topics of the thesis, Digital Twin and Building Operation, were introduced and explored in the literature review systematic literature review was performed. The goal of it was to answer the sub-questions of the problem formulation, particularly „*What does the Digital Twin concept entail?"* and "*What is the current status of digitization in operation and maintenance phase of the building?"*.

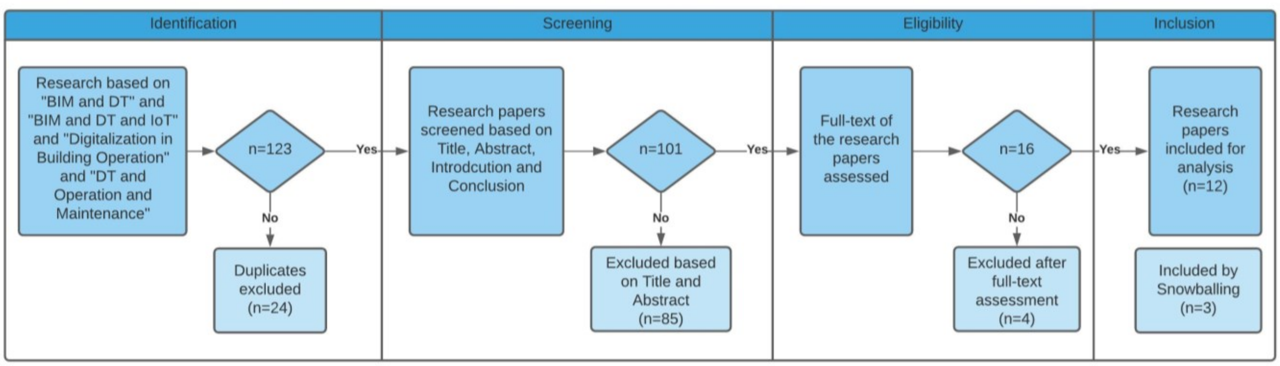

Figure 11: PRISMA flow diagram visualizing the research paper selection process for analysis

As mentioned in chapter 2.2.1, the systematic literature review was performed based on the PRISMA framework, and the process is shown in Figure 11. Aalborg University Library called Primo were used and the keywords that were defined during the research are "BIM and DT", "BIM and DT and IoT", "Digitalization in Building Operation", and "DT and Operation and Maintenance". The search in Primo resulted in 123 research papers, and at the end of the selection process (Figure 11), 12 research papers were selected for the analysis and 3 research papers were added by the snowballing method.

4.1.1. THE FINDINGS ON DIGITIZATION IN BUILDING OPERATION

To find the answer to „ *What is the current status of digitization in the operation and maintenance phase of the building?"* the results of the systematic literature review are summarized in Table 3 and Table 4. In Table 3, seven research papers are summarized based on two criteria, the findings on digitalization in building operation and the use of digital technologies, and finally, challenges of implementing digital technologies. In Table 4, the current research and achievements in the digitalization of building operation are collected from the different research papers.

Source	Findings on digitalization in building operation (a) and the use of digital technologies (b)	Challenges of implementing digital technologies
(Bosch-Sijtsema, et al., 2021)	(b) Digital technologies support data-driven decision making that is based on improving productivity, visualization and simulations. (Bosch-Sijtsema, et al., 2021)	(1): lack of competence (2): the current working methods of the industry (3): lack of trust in collected data and insight on how to use it for the right context (4): lack of digital strategies and supporting the leadership in implementation of digital technologies
(Krämer & Besenyői, 2018)	(a) (1): Benefits of BIM in building operation is recognized, on the contrary the practical usage of BIM in FM is scarce. (2): There are uncertainties about how the finished As-Built model for FM purposes should look like and what information should it contain. (Krämer & Besenyői, 2018)	(1): the excessive effort of data capturing in existing buildings (2): creating As-Built digital models for FM from scratch (3): keep the As-Built model up to date
(Wong, et al., 2018)	(a) The potential use of digital technologies throughout the whole life cycle of the building attracts attention in the AEC industry. Furthermore, a supportive data management system for building operation that can support and integrate information and data that the project stakeholders generate can be beneficial in the maintenance phase. (Wong, et al., 2018)	(1): lack of clear standards and protocols to define the integration level requirements (2): lack of understanding and skills of BIM (3): data ownership and copyright protection issues in BIM (4): lack of end-user involvement (5): most BIM models do not contain adequate and accurate data for FM (6): lack of real-life examples of BIM application for FM

		(7): interoperability between BIM technologies (8): less consideration of the relevance of maintenance requirements during the design phase
(Koch, et al., 2019)	(a) (1): Digitalization in FM will necessitate integration between competencies, technical digitalization, management and organization of digital FM. (Koch, et al., 2019) (2): Recent research focuses on CAFM (computer-aided facility management) systems implementation and/or use of BIM, but its contribution is limited in the current digitalization of FM. (Koch, et al., 2019)	(1): need of digitalization strategies and operational hybrid practices (2): the need to prepare organization, management and proficiency for digitalization (3): further development of standards and classification systems (4): BIM models are insufficiently integrated
(Motawa & Almarshad, 2013)	Analysis and integration of various kind of information and knowledge is required for decision making for building operation, that is generated by the different stakeholders.	(1): supportive facilities for technology and management aspects (2): current BIM applications cannot use the competencies of knowledge systems for building operation completely
(Agarwal, et al., 2016)	(a) The AEC industry is behind adopting digital technologies and still uncoordinated between the site and the office. (Agarwal, et al., 2016)	(1): Technical challenges
(Becerik-Gerber, et al., 2012)	FM relies on various and incompatible systems to manage building operation because the management systems are separate and independent of each other.	(1): unclear how BIM could be implemented and (2) what are the requirements for prosperous implementation for BIM in FM

Table 3: Summarizing the systematic literature review results about the current status of digitalization in Building Operation

Table 3 focuses on the researchers' view on digitalization and the use of various digital technologies, and the challenges of digitalization in building operation. It has been mentioned before that, in general, the AEC industry is slower in adopting more advanced digital technologies (Agarwal, et al., 2016), than other industries; furthermore, the implementation of BIM is more progressive during the design and construction than in the operation and maintenance phase of building life cycle. (Krämer & Besenyői, 2018) described in their research paper that for building operation the benefit of BIM is acknowledged, but the practical use of it is infrequent, and according to (Wong, et al., 2018), the potential of implementing digital technologies throughout the whole life cycle of the building attracts attention in the AEC industry.

On this note, it is not defined how the As-Is model for FM purposes should look and what information it should contain. Consequently, to fully benefit from digitalization in FM integration between competencies, technical digitalization, management and organization of digital FM is unavoidable (Koch, et al., 2019). (Wong, et al., 2018) described that with the help of a supportive data management system for building operation that can support and integrate information and data generated by the project stakeholders, it can be beneficial in the maintenance phase.

To follow up on the findings of (Koch, et al., 2019) and (Wong, et al., 2018), recent research concentrates on the use of BIM and/or CAFM systems implementation. However, unfortunately, its contribution is limited in the current digitalization of FM (Koch, et al., 2019). With the support of digital technologies, data-drive decision-making can be achieved based on improving productivity and visualization and simulations (Bosch-Sijtsema, et al., 2021).

The following table (Table 4) is about what research and digital technologies have been implemented for building operation.

Source	Current research and achievements in the digitalization of BO
(Li & Becerik-Gerber, 2011)	This paper described that RFID-based location detection identification of facility items for repair or maintenance is recognized to be beneficial to improve the efficiency of maintenance management.
(Su, et al., 2011)	This paper established a BIM-based FM system where the most current maintenance-related information, problem descriptions and solutions can be followed, managed and visualized in 3D.
(Issa & Liu, 2012)	The authors developed a system that enables automatic and real-time information updates during the maintenance phase from the BIM database in order to provide a connection of information between design and FM teams.
(Love, et al., 2013)	A Building Information Model developed to LOD500 could be taken into account for FM, as a result of containing geometry and information to help operations and maintenance tasks.
(Motawa & Almarshad, 2013)	The authors came up with a framework that gathers and incorporates the information on operations, maintenance, knowledge of the building during and after the maintenance phase.
(Kelly, et al., 2013)	This paper describes how facility managers find it complicated to use and access some handover information as a result of inadequate and incomplete received information.
(Kelly, et al., 2013)	Governments all around the world suggest that BIM is a strategy to focus on the inefficiencies that have an effect on the AEC industry and improve productivity.
(Wang, et al., 2013)	In this article, FM, BIM, and BMS are combined to enable equipment information monitoring, dynamic data display, energy saving analysis, etc.

(Liu, et al., 2014)	This research paper indicates that facility managers might not be included during the design phase since the FM team is not yet established.
(Motamedi, et al., 2014)	This paper demonstrated that BIM models have the function to visualize objects. These competencies enable FM technicians to view maintenance object in 3D. It is possible to solve maintenance issues by the use of cognitive and perceptual reasoning skills.
(Motamedi, et al., 2014)	In this article, visual analytics has been applied to detect abnormal thermal conditions in a building.
(Ammari & Hammad, 2014)	In this article, an integrative BIM-based system has been developed. In this system, instant data can be gathered to investigate building information with the implementation of mixed reality and different visualization techniques.
(Gheisari, et al., 2014)	The authors described the integration of BIM and mobile augmented reality technology to develop a scheme where FM practitioners can get involved in an intuitive natural interaction with the mobile interfaces to access the needed information effectively.
(Li, et al., 2014)	This article describes the implementation of BIM for real-time monitoring of the building's status and the maintenance of a database for asset maintenance data.
(Dong & Lam, 2011), (Newsham, et al., 2017), (Shen, et al., 2017)	They discussed that adequate detection of occupancy pattern is recognised to be relevant so correct decisions can be for building services and energy control.
(Kim & Hong, 2017)	BIM provides object-based 3D visualization data necessary for FM data management; furthermore, data identification and acquisition become more effective and faster for object-based FM systems with BIM support.

Table 4: State of Art applications of digital technologies for FM

4.1.2. COMPONENTS OF DT

In order to find the answer to „*What does the Digital Twin concept entail?"* the results of the systematic literature review are summarized in Table 5. In Table 5, eight research papers are summarized based on three criteria; their research area and/or use case, how the authors describe the Digital Twin, and finally, what DT components or attributes are defined.

Source	Research area (a) and use case (b)	Description of DT	DT components (c) or DT attribute (d)
(Khajavi, et al., 2019)	(a) Comparison of BIM and DT, as well as the exploration of the benefits and boundaries of DT. (b) Data collection with the help	Visualization in DT can depend on a 3D model of the building, and the DT can implement different sensor networks to develop a real-time view of the building. This view supports real-time analytics, improved decision	(c) (1): BIM, which contains data, 3D design and documentation (2): Wireless Sensor Network (Real-time operational and Big Data) (3): Data Integration

	of WSN on the office building façade of Aalto University (Finland)	making and building efficiency. (Khajavi, et al., 2019)	and Analytics (Machine Learning)
(Camposano, et al., 2021)	(a) Exploring how AEC/FM practitioners describe the Digital Twin of a building (b) conducting interviews with AEC/FM stakeholders	The AEC industry stakeholders are considering integrating BIM tools and other technological advancements associated with IoT, for instance sensors or cloud computing, to develop a Digital Twin. (Camposano, et al., 2021)	(d) (1): Time range and scope (2): Aim and purpose level of abstraction and precision (3): Synchronization (4): Technological components (5): Actor independency (6): Value proposition
(Sun, et al., 2020)	(a) The authors described a theoretical five-dimensional model of DT, which in practice is still abstract to be used as a guide for developing a DT system, but they analysed the possibility of implementing the 5D DT model.	People implemented the DT of mapping assets to perform physical asset operation simulation and perform various experiments and simulation of different scenarios. (Sun, et al., 2020)	(c) (1): Physical entity (2): Virtual entity (3): Digital Twin data (4): Service system (5): Connection
(Küsel, 2020)	(a) The authors present a Model-Based System Engineering framework to support developing a DT of Real Estate.	A DT is learning and synchronizing with the physical model while it is collecting data from the physical model (physical twin) by using advanced technologies, like ML. (Küsel, 2020)	(c) (1): User/owner eco-system (2): Virtual asset dashboard (3): Analytical tools (4): Virtual asset (5): Data acquisition tools and external data sources (6): Physical asset
(Lu, et al., 2019)	(a) The research paper is about presenting a system architecture for the development of dynamic DTs in building levels to be able to integrate heterogeneous data sources and support intelligent data query and provide better decision-making processes. (b) developing a dynamic Digital Twin at Cambridge campus	A Digital Twin is a digital model that represents the physical asset and mirrors the real-world behaviours of the physical asset. (Lu, et al., 2019)	(c) Four levels of the dynamic DT system architecture (1): Data acquisition (2): Data transmission (3): Data and model integration (4): Application (Lu, et al., 2019)

(Dawkins, et al., 2018)	(b) Creating a DT of the new UCL Campus at Here East on the Queen Elizabeth Olympic Park to perform a practical investigation using real-time data and advanced 3D visualization.	The Digital Twin indicates the connection of a physical system and its digital representation in a virtual environment, where relevant changes in the physical system can be discovered and results in a data flow that will align the change in the state of the digital doppelganger. The information which DT develops can be looped back into the physical system. (Dawkins, et al., 2018)	(c) the study investigates, how (1): BIM (2): Real-time data from IoT sensors (3): BMS to develop an operational DT.
(Peng, et al., 2020)	(b) The authors present a proposal of DT of a hospital building by the continuous life cycle integration concept.	The goal of the DT is to represent the real-time information between the physical and virtual models. The visual management features are helping the managers of the physical asset monitor the operation status and make optimal decisions. (Peng, et al., 2020)	(d) (1): enabling life cycle monitoring (2): support optimal decision making (3): intelligent device integration (4): data analysis and the results are looped back into reality
(Wahbeh, et al., 2020)	(a) This research paper aims to clarify the DT concept by analysing the definitions of DT in the AEC industry and proposing the DT concept as an aim for a project-based learning approach in a didactical setting.	Digital Twin is a digital replica of a building's structure and behaviour with bilateral connections between the physical and virtual model, and these connections provide information about control commands, data usage and analysis, status etc. Furthermore, DT can have various forms based on LOD, degree of automation, and type of connections and information. (Wahbeh, et al., 2020)	(d) Fundamental technologies to develop a DT: (1): reality capturing and scanning (2): BIM (3). IoT (4): Data management and visualization

Table 5: Summarizing the systematic literature review results about the components of Digital Twin

The Digital Twin concept has been introduced from the historical overview, through the theoretical approach and DT in the AEC industry. It has been mentioned that Digital Twin is not a technology, but rather a concept, which implicates the integration of different advanced technologies; furthermore, it does not have a standardized definition. Under these circumstances, in the case of this thesis, it is significant to elaborate on how DT is described by the stakeholders of the AEC industry as well as to find the common features of definitions of DT.

In general, four things are discussed in the research papers to describe the Digital Twin, namely the “basic” description of DT, visualization, implementing IoT and other advanced digital technologies, and its purpose. Digital Twin is described as a digital model, which represents the physical entity and mirrors the real-world behaviours of the physical entity (Lu, et al., 2019) as well as it is a digital replica of a building's structure and behaviour with bilateral connections between the physical entity and virtual model, and these connections provide information about the current state of the building (Wahbeh, et al., 2020). Furthermore, a DT indicates the connection of a physical system and its digital representation in a virtual environment (Dawkins, et al., 2018). As a result of the bilateral connection between the physical entity and virtual model, a DT enables synchronization while it collects data from the physical model by advanced technologies, such as ML (Küsel, 2020) and IoT; also, the stakeholders are investigating the contingency of integrating BIM tools as well (Camposano, et al., 2021). The implementation of various sensor network networks supports developing a real-time view of the building, which supports real-time analysis, improved decision-making, and later on improved building efficiency (Khajavi, et al., 2019). Thanks to the data flow, the important changes are detected in the physical entity, which later on is aligned in the state of the Digital Twin, and the data can be looped back into the physical system (Dawkins, et al., 2018).

The purpose of the Digital Twin is to represent the real-time information between the physical entity and virtual models (Peng, et al., 2020); furthermore, it can be implemented to perform various experiments and simulations of different scenarios (Sun, et al., 2020). Visualization in DT can rely on a 3D model of the building (Khajavi, et al., 2019), and the visual management features are providing help to monitor the operation status and make an optimal decision (Peng, et al., 2020); moreover, DT can have various forms based on LOD and degree of automation as well as the type of connections and information. (Wahbeh, et al., 2020)

(Dawkins, et al., 2018) described a Digital Twin at Here East, an innovation and technology campus in Queen Elizabeth Olympic Park in East London. The Olympic Park now accommodates studios for BT Sport, Infinity data center, Plexal innovation hub for small enterprises, and two university campuses, namely Loughborough University and UCL. They investigated how LiDAR data and BIM could be incorporated with real-time data from IoT sensors and the BMS to set up an operational Digital Twin. In their study, they analyzed the connection between the building and its expended environment. The investigation occurred by integrating the CASA's ViLo model of the Olympic Park, allowing additional research about the challenges of real-time data integration, development of various temporal and spatial scales and the required level of abstraction. They also considered the opportunity of living and working with the DT technology daily in the future, as well as its impact on human behaviour. To achieve this, they allow the students and staff to interact with the DT. They installed environmental sensor boxes at the campus of UCL and ran simulations for six months. The purpose of the collected data was to determine relationships and patterns between the environmental parameters over a certain amount of time. The visual data analysis occurred in 3D and near real-time by taking advantage of the rendering potential of the Unity game engine, which allows visual inspection of features that are not visible in the day-to-day performance of the building.

Figure 12 represents what the Digital Twin concept entails. From the analysis of the above-mentioned research papers, it can be concluded that the DT concept can be divided into two sections, the physical end, where the occupants can interact with it and the virtual end, where data

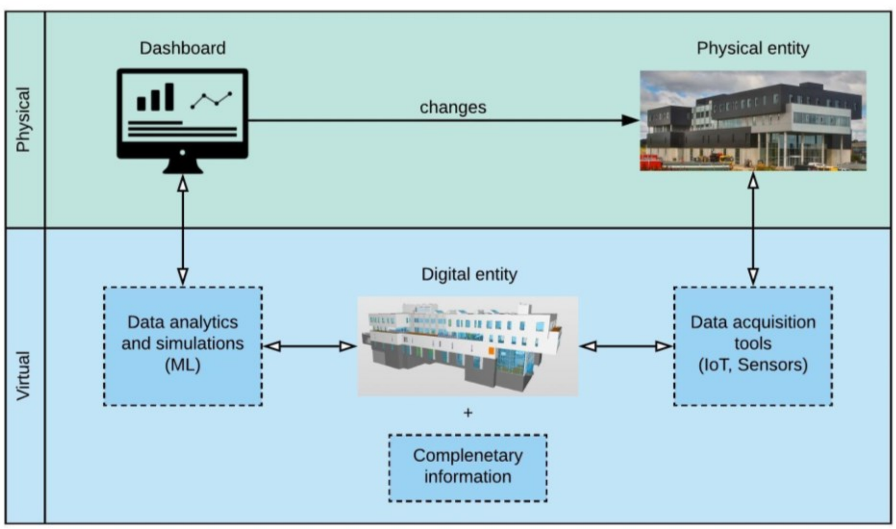

Figure 12: Components of the Digital Twin based on the systematic literature review

collection, process, management, simulations and analytics are accomplished. The physical end contains the physical model and dashboard, and the virtual side contains the data acquisition tools, virtual model and data analytics and simulations tools.

The data is collected from the physical entity and external sources, and then collected data is transferred into the virtual model, which replicates the AS-IS condition of the physical entity. Various analytics and simulations are run in the virtual model, and the outcomes are displayed on the dashboard. The flow of the DT concept starts on the physical side with the physical entity and goes through the virtual side and goes back to the physical side (dashboard), and as a final step, the result of simulations can be implemented in the physical entity. Furthermore, the steps are described in details:

1. **Physical entity:** The building
2. **Data acquisition tools:** For the proposed framework, an IoT-enabled wireless sensor network (WSN) is suggested to be used to acquire data from the physical asset in the form of temperature, humidity, motion detection, light meter, CO2, AC current meter etc. IoT enables WSN to support data uploads from other sensors deployed at distributed locations of dispersed assets, and its scalability supports a large number of assets in buildings (Lu, et al., 2019). Data is also obtained from the smart electric meters with information such as electricity consumption, voltage levels, power factor and current. The data provided is in near real-time and updated at regular intervals.
    - **Sensors:** The visualization of the DT for a building can depend on a 3D CAD model that is extracted from BIM or another custom 3D model. The DT of the building is implementing the use of different sensor networks to provide a real-time view of the physical entity. the real-time view provides a dynamic view that supports real-time analytics, enlightened decision making, efficient building operation. (Khajavi, et al., 2019)
3. **Virtual model:** the virtual model is the carrier of the collected data; consequently, it is the core of the Digital Twin. The virtual models exist in a variety of data, the essential data is in 3D space, and other data is attached to this data. (Sun, et al., 2020) In order to support more functions, the virtual model is supplemented with complementary information. Various digital models can be adapted for different

purposes; for example, an energy model could be used for simulating energy performance. (Lu, et al., 2019)

4. **Analytics and simulations** can be done by advanced technologies, such as AI and ML (Sun, et al., 2020) (Küsel, 2020); these advanced technologies would provide better decision-making management (Lu, et al., 2019). By conduction analytics and simulations based on real-time data, the changes can be implemented in the physical entity, and the AS-IS condition of the building can be updated in the virtual model. (Lu, et al., 2019)

5. **User interface:** The user can have access to the virtual model; moreover, it contains data records via a 3D dashboard, and it can import various file formats, questions can be inquired. (Küsel, 2020)

6. **Bilateral connections:** One of the most common facts about DT that the virtual entity is the digital mirror of the physical entity. Yet, when the DT is working, from the dynamic aspect, the outcomes of the virtual entity need to be looped back to the physical entity to influence the change in the physical entity. As a result, the connection between the physical and virtual entity is bidirectional. (Sun, et al., 2020)

4.2. INTERVIEW ANALYSIS

In order to answer the last sub-question of the problem statement, *"What value can it provide to the various stakeholders involved?"* interviews had been conducted, and the findings have been supplemented with systematic literature review.

First, the interviews have been analysed with the framework method that is described in 2.3. Data Analysis and afterwards the Value Proposition Canvas has been implemented to visualize the key findings and pair them up with Digital Twin values, which was found in the systematic literature review.

4.2.1. INTERVIEW ANALYSIS WITH THE FRAMEWORK METHOD

Three interviews have been conducted:

- The first interview included two people being interviewed together. These people were the Team Leader of the Campus Service and a Technician at a university. They introduced the Building Management System of the university to demonstrate an example of a BMS.
- The other two interviews were conducted to support the general problem statement of the paper. These interviews were conducted with a Product Developer and a Product Owner and Team Leader of Consultants at two Danish companies working on developing FM software to gather information about their insights and perspective about BMS and values in building operation.

The semi-structured interview guide was based on the idea to gain knowledge about the roles the interviewees are playing in building operation, the components and functions of the BMS/FMS they are working with and future perspective on advanced technologies such as IoT, ML, AI etc. Few questions have been set, and the interviewer was open to having follow-up questions to get better insight into how DT could add value to building operation.

As it was mentioned, the *2.3. Data Analysis*, the framework method had been used to analyse the interviews. In this section, in Table 6 and Table 7, the result of the analysis is briefly described (step 4 to step 7).

In step 4 (Developing a working analytical framework), the themes are defined as:

- Role
- System
- Functions
- Data
- Limitations/Challenges
- Visualization

- Connection to other systems
- Future perspective and views

Based on the defined themes, as step 5, 6 (Applying the analytical framework and Charting data into the framework matrix), the columns of Table 6 and Table 7 was created, and the rows refer to the individual interviews.

1. Team Leader of the Campus Service and a Technician (The transcription of the interview can be found in Appendix - Interview 1)
2. Product Developer (The transcription of the interview can be found in Appendix - Interview 2)
3. Product Owner and Team Leader of Consultant (The transcription of the interview can be found in Appendix - Interview 3)

	Role	System (a) and modules (b)	Functions	Data
1	Team leader and Technician	(a): BMS (b): heating system, ventilation, cooling, light and fire alarms	remote monitoring, an overview of the functions and areas, alarm notifications, locking abnormalities, automated temperature change, data exchange	Real-time data
2	Consultant and Developer	(a): FM system developed by the company (b): helpdesk, assets, documents	managing a different aspect of FM, integration of systems, geometry is a placeholder where data is linked together	Real-time data by intervals
3	Product Owner and Team Leader of Consultants	(a): FM system developed by the company (b): task and resource management, calendar system, day-to-day task of service	predict maintenance cost	Real-time data

Table 6: Interview analysis based on the Framework method (part 1)

As a summary of Table 6 and Table 7:

The main BMS system modules are in a university is the operation and maintenance of the heating, ventilation, cooling system, light and fire alarms. They work with real-time data and have 2D floorplans as visualization. The BMS functions are focusing on remote monitoring, which is very useful during the recent pandemic as the system can be operated from home; alarm notifications, that are nowadays (again due to the pandemic) prioritized, so the technicians are getting a notification about the highly prioritized alarms; they have the possibility to adjust temperature set points, lock the temperature abnormalities for a certain amount of time, as well as automatic temperature change. The university's BMS is connected with the energy system, booking system and fire system, which means the different systems can exchange data, for instance, energy measures from the BMS are sent to the energy system, or when a fire is detected, the fire system sends a notification to the BMS or the booking system notifies the BMS if a room is booked or not, so the BMS can adjust ventilation and the heating system.

The companies are working on their own FM solutions, where interviewee 2's solution is focusing on different aspects of FM, meaning that their system consists of a Helpdesk module, where the users of the building can report if something is wrong with the building; Asset module, which is dealing with the different components and these components can be linked together; and lastly a Documents module. These modules can be connected so that the information can flow across them. This FM solution can be integrated with different systems, meaning that certain data is their system (system A), that is exposed through an API, and that data can be extracted from their system by someone (B) when B is connected to system A's API. Their system works with real-time data in intervals; the intervals are set, so the system users will not crash the system by uploading data every millisecond. This FM solution has 3D visualizations.

Interviewee 3's FM solution supports Helpdesk, Task and Resource management, calendar system and day-to-day tasks of service employers, and the integration of 2D and 3D drawings. Their system supports real-time data as well; furthermore, one of the premises of their FM solution is the ability to predict the maintenance cost of the building, they developed a 10 and/or 30 years plan, and the result can be visualized. Later on, they are planning to use sensors to automatize the maintenance of the maintenance plan. Their FM solutions can be connected with an ERP system and some organizational systems.

	Limitations/challenges	Visualization	Connection to other systems	Future perspectives
1	The system cannot lock everything (30 days), future performance prediction, resources, 3D visualization	2D floorplans	The energy system, booking system, fire system	3D visualization, IoT sensors,
2	development takes more time than its actual value, lack of standardization of integration, resources vs value and man-hours,	3D		DT would grow into a software, ML and AI have lots of potential automation.
3	digitalization, lack of registered data, lack of focus on advanced technologies, keeping maintenance plan up to date, resources and man-hours	3D	NTI-FM integrated with ERP systems and organizational systems	Predictive maintenance, digitalize data so the complex data can be turned into visualization, improving integration

Table 7: Interview analysis based on the Framework method (part 2)

During the interviews, the limitations of the BMS/FMS and the challenges of implementing advanced technologies such as IoT, ML and AI were discussed. Interviewee 1 explained that their system cannot predict future performance, only to some degree; for instance, the heating system can predict how it should regulate in few days based on the outdoor temperature and data within the last three-four day. They do not have 3D visualization of the university in the system; they have mixed opinion on having 3D visualization one of them says it is not needed, the other expresses interest in having 3D visualization as it a "new thing" and to some extent, it would be useful. However, their main motto is "keep it simple", and they are happy with what they have.

Since interviewee 2 and 3 are developing their own systems, they provided information about the challenges of digitalization and implementing DT, advanced technologies and digitalization. Interviewee 2 reflected that the main challenges are the lack of standardization of integration and keeping the geometry updated. He described that there is no standardization on the integration between the different components of the building, as they have one way of doing it and the others, who would like to integrate their component, could have another way and a developer is still needed to do it, moreover, usually, there is a 3rd party software, as a middle ground between the integrations to support the data exchange. Consequently, there is no solution that can cover everything because considering the variety of use cases in FM and comparing the development to value, in some cases, the development takes more time than the value it provides.

Interviewee 3 reflected that the main challenges are digitalization, lack of registered data, lack of focus on advanced technologies, keeping maintenance plan up to date. He mentioned one client who has IoT implemented in their buildings, where the data collected by the different sensors is gathered in a server and later on sent to them, but it does not work perfectly, especially not to maintain the maintenance plan. He indicated that the problem is with digitalization Moreover, most clients have certain data on paper and are not registered in the system, and some clients have all their data registered in the system. Furthermore, the more significant challenge of implementing advanced technologies is that the industry lacks focus on this area, and for instance, keeping the maintenance plan has a bigger priority than the advanced technologies.

All three interviewees indicated that resources, both financial and man-hours, are a leading limitation for implementing advanced technologies. Interviewee 1 implied that the advancement and intelligence of BMS of a building depend on how much money there is for it, and it is quite expensive to keep a 3D model updated. Interviewee 2 indicated that it is important to consider resource vs value, as it takes a lot of man-hours to set up a system, and at the early stages of the process, the maintenance of the system is neglected, and the maintenance also requires man-hours. Thus, the value needs to be worthy for the dedication of the resources and man-hours. Interviewee 3 implied that it needs to be clear for the customer if he wants a high level of degree 3D model that needs adequate workforce and financial resources for its maintenance.

Lastly, future perspectives were discussed to gain knowledge about how they see building operation in the future and how they would improve it. Interviewee 1 thinks that 3D visualization could be useful in the future, but his main interest was the implementation of IoT sensors because the installation of cables and communication between the existing room and newly constructed room is the old-fashioned way; furthermore, the use of IoT sensors can expand the scope of data acquisition and energy consumption could be improved. According to interviewee 2, there is a grey area between a good software, good UI and ML and AI, but there could be great potential in this area, such as some level of automation; he has not seen good use cases in the AEC industry so far. Interviewee 2's view on Digital Twin that it would slowly grow into a software moreover it does not seem to be possible to create one DT for all purposes, especially in FM where 80% of work is spent with something else than working with digital things, and there are minimal resources for a DT. Interviewee 3 sees DT as the future, considering that the complexity of data is definitely increasing, and it is much easier to for a person to identify the different objects and elements by looking at them in 3D rather than seeing it in a list. To this extent, if this data is digitalized, complex data is turned into visualization, which people can easily understand. On the contrary, he indicates that the maintenance of these digital models is overseen. Another thing that should be improved is the integration of certain functions.

4.2.2. ADDED VALUE TO BUILDING OPERATION

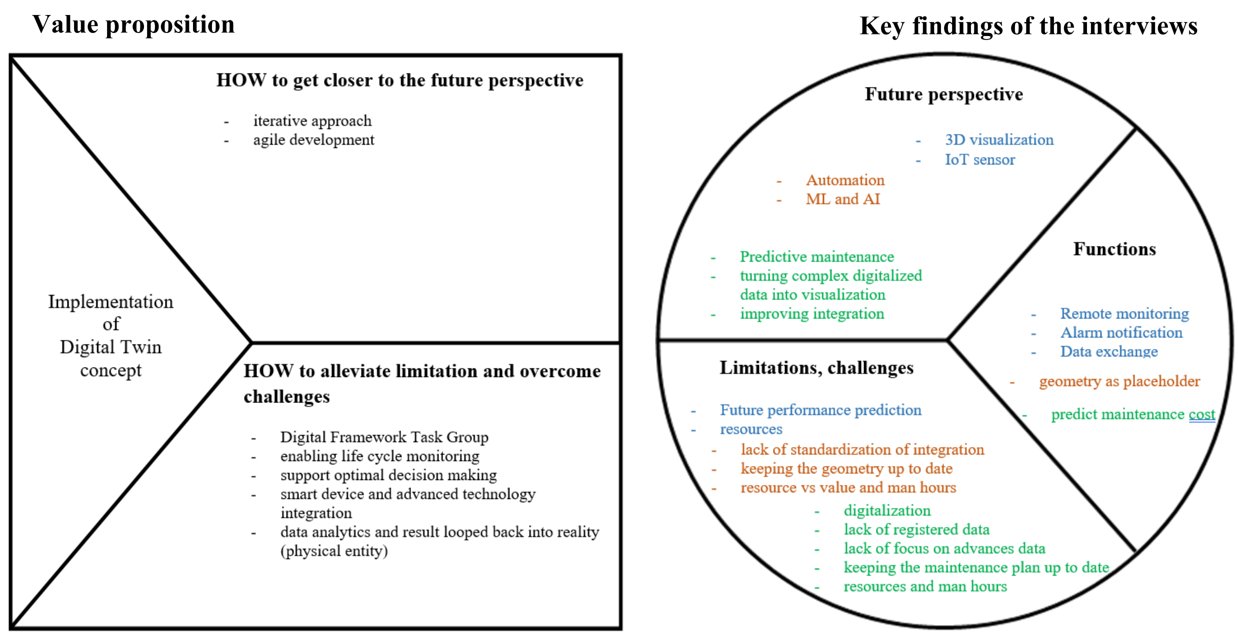

Figure 13: Value proposition canvas implemented to visualize the findings of the systematic literature review and interview analysis

Figure 13 visualize step 7 (Interpreting the data) of the framework method. In this case, the Value proposition Canvas (previously described in chapter 2.4) has been implemented to answer the above-presented sub-question. The “circle” represents the customer profile, which in this case are the key findings of the interviews (blue represents Interview 1, brown represents Interview 2, green represents Interview 3), namely functions, future perspectives and limitations/challenges of building operation and FM. The “square” represents value proposition, which describes the particular methods and attributes of DT that have been acquired from research and the systematic literature review, which in this case are the ways and methods to support the achievement of future perspectives, attributes of DT that would alleviate the limitations and challenges of building operation and FM and the lastly the end goal, which is the implementation of Digital Twin concept.

The listed limitations and challenges in Figure 13 supplement the findings of the systematic literature review (chapter 4.1.1); furthermore, to alleviate them, the implementation of the Digital Twin concept appears to be beneficial in this case. Various attributes of it could support the alleviation of the challenges and limitation, such as enabling monitoring the building during its life cycle and the ability to perform data analytics and simulations with the help of advanced technologies based on data that is accumulated via sensors (IoT sensors) and from external sources (for instance weather data), that would further improve decision making. In addition, the DT attributes that would support the alleviation are in relation to the listed future perspective, as the advanced technologies, predictive maintenance etc., are the technologies and functions that the DT is intended to use and perform (chapter 4.1.2).

However, it is necessary to consider realizing the reason and purpose of implementing advanced technologies and DT and having the needed resources (not just financial, but man-hours as well). Because in general, it seems to be a great solution, but on the other side it would not be fully beneficial due to its complexity (Interviewee 2 and 3 referred to this as resource vs value). Thus, the benefits of DT and advanced technologies for a given purpose should be well explored.

At the first glimpse, DT and advanced technologies may seem to be more complex than the value that they could provide at this moment. As a reason, it is necessary to choose a sufficient implementation approach to benefit from it entirely. Sufficient approaches, in this case, could be an iterative approach and the adoption of the agile development process.

(Dooley & Camposano, 2020) described the iterative approach to implement the DT concept, where small steps are made forward with the implementation; also, the most straightforward use cases are considered first. Its goal is to find the sweet spot technologies that will create enough value, which will balance the needed resources to create and operate the Digital Twin. One of the advantages of the iterative approach is the learning during the progress of implementing DT and recognizing the fine details of the individual use cases while doing it. This approach requires the organization to be agile and lean. During the process, every version of the

DT gets feedback from the significant stakeholders to know if their requirements are fulfilled and ways to improve them. (Dooley & Camposano, 2020)

5. DT IMPLEMENTATION PROCESS

In this chapter, the answer to the main question of the problem statement *"How to enhance the implementation of Digital Twin concept in Building Operation?"* is developed. Based on the key findings of the systematic literature reviews and the interview analysis above, a DT implementation process for building operation is presented, which has been inspired by different previous research papers.

5.1. PROCESS OF IMPLEMENTATION

Based on the findings of the systematic literature review and the interviews, it is concluded that an iterative approach is the most beneficial for implementing the Digital Twin concept. As (Dooley & Camposano, 2020) described, an iterative approach needs to be agile and lean, where lean supports continuous and additional improvement and attempts to reduce non-value-adding tasks; moreover, in agile (Figure 14), there are iterations to develop the needed improvements and give a working product to the end-users within a shorter period of time, enabling feedback and evaluation after a certain amount of use. The application of both lean and agile will contribute to flexibility and adaptability to adjust FM requirements and information availability. (McArthur & Bortoluzzi, 2018)

Figure 15 describes the implementation process of the Digital Twin for building operation in general. To develop this process, the Digital Twin application process by (Küsel, 2020) and twelve steps of BIM implementation for FM by (Nyvlt, 2020) as well as the agile development process (Figure 14) were considered.

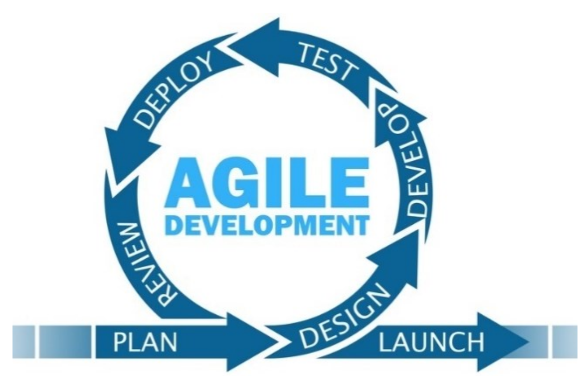

Figure 14: Agile development process (D'Ambra, n.d.)

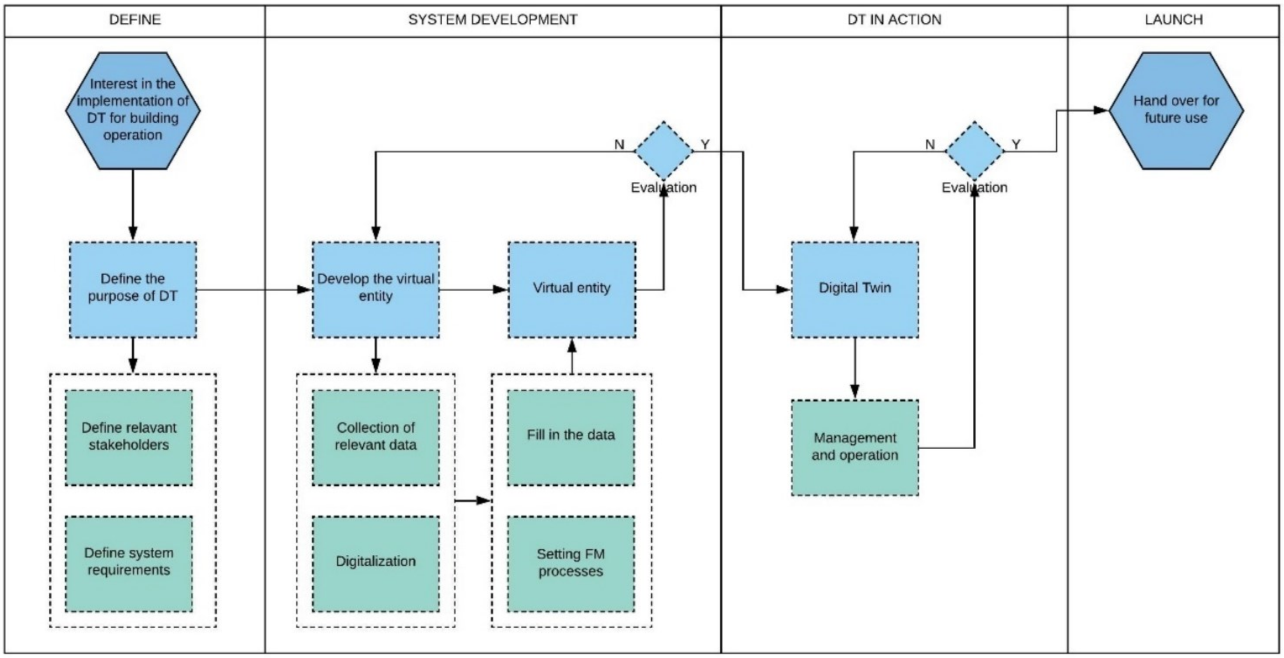

Figure 15: Lean-Agile Digital Twin implementation process

The Lean-Agile implementation of DT for building operation has four main stages (Figure 15), precisely Define, System development, DT in action, Launch. The different stages are described in detail in the following paragraphs.

In the **Define** stage (Figure 17), the organization decides that it wants to implement the DT for building operation. Furthermore, the purpose of the DT and the FM goal(s) are defined so that the DT will have a clear purpose, for instance, energy consumption optimization, maintenance plan management, space management etc. with the help of the relevant stakeholders and the system requirements are specified as well. Relevant stakeholders could be a Digital Framework Task Group, where people from government, academia, and industry come together to share insight and provide help to develop and manage the DT. The DTFG would be an external stakeholder. The internal stakeholders are the ones within the organization who would like to implement and manage the DT; they are the FM team and technicians. These three stakeholders are "sit together" and define the system requirements, including the need for digitalization and the relevant data for the given purpose. Part of the digitalization is to evaluate the existing drawings and documentation to know what is already digitalized and what needs to be digitalized. After the system requirements are specified, the process can go forward into the next stage.

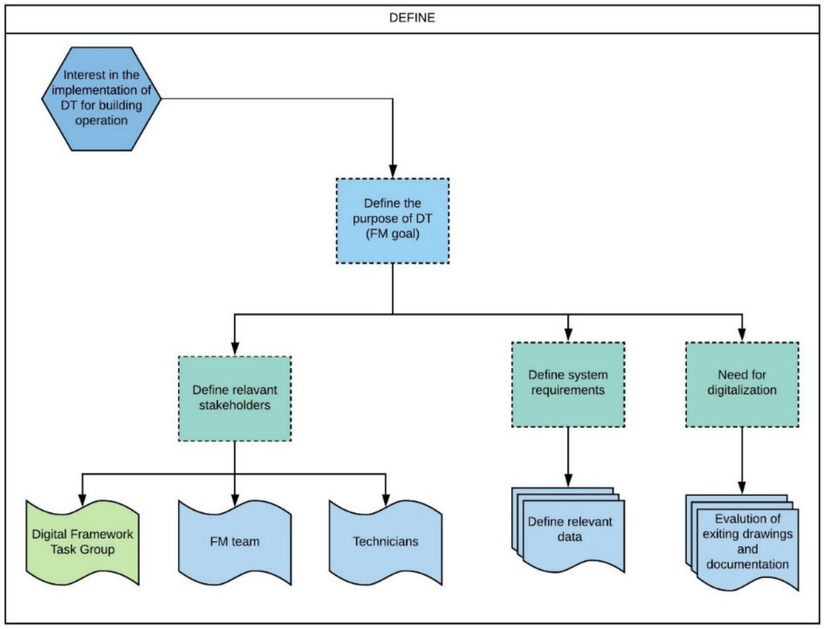

Figure 17: The DEFINE stage of Lean-Agile DT implementation process

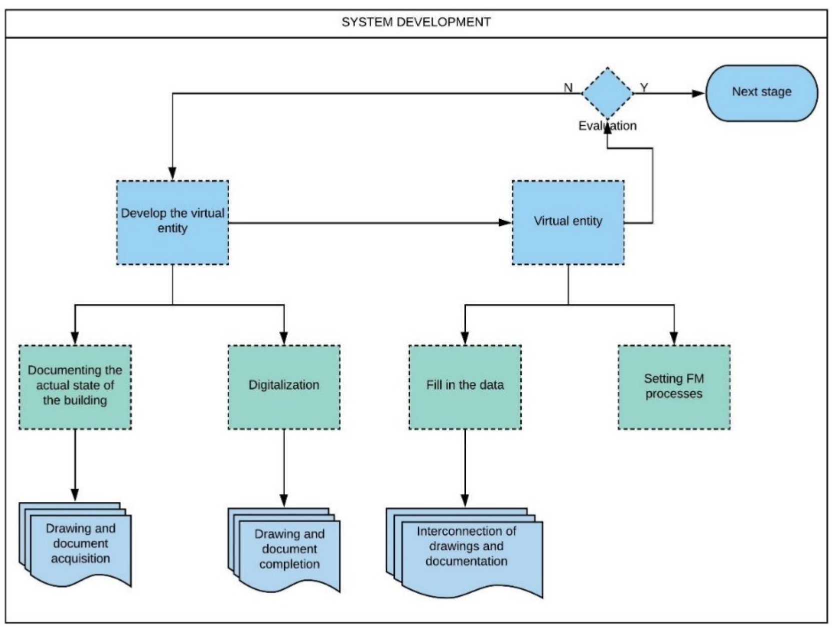

Figure 16: The SYSTEM DEVELOPMENT stage of the Lean-Agile DT implementation process

The next stage is the **System development** stage (Figure 16)**,** where the virtual entity of DT is developed. Moreover, the building's current state is documented, so the drawings and documents are collected, and these drawings and documents digitalized, so it can be used in the virtual entity. After the virtual entity is created, it is filled with the relevant data, the drawings and documents are interconnected. Furthermore, the FM processes needed for the given purpose are set in the virtual entity. At the end of this stage, the virtual entity, with the data, interconnected drawings and documents, and the set FM processes, is presented to the internal stakeholders; therefore, they can give feedback and express if additional development is needed.

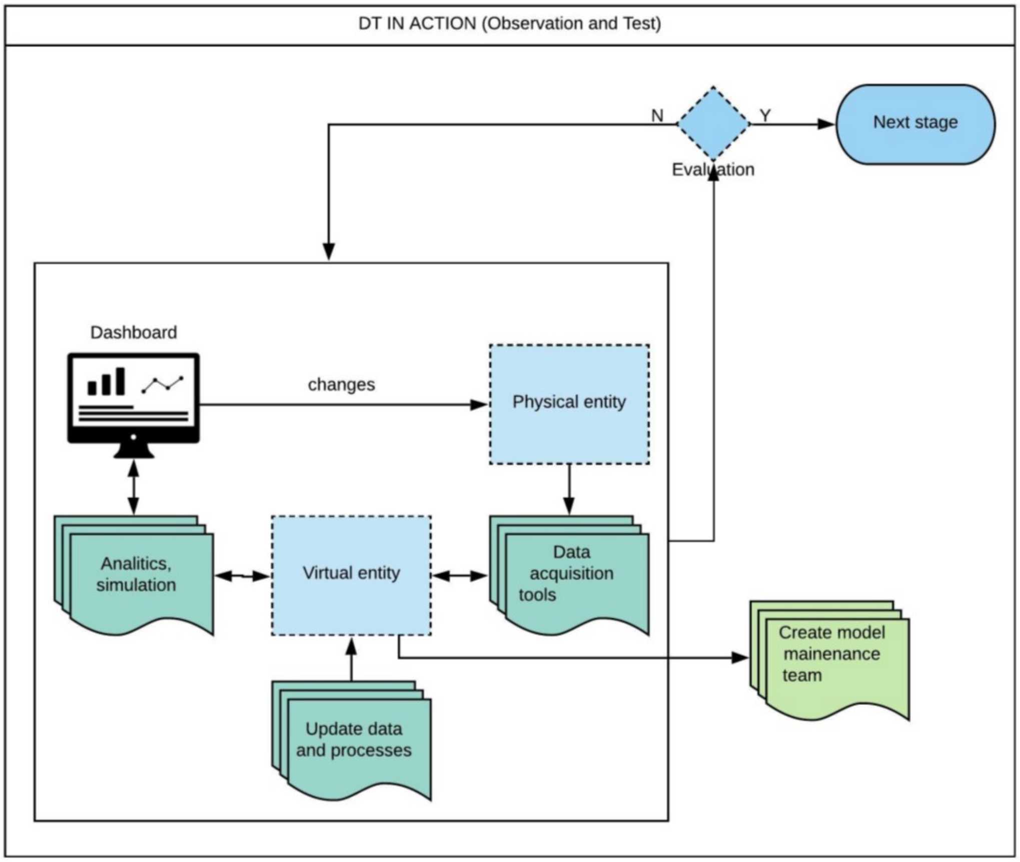

Figure 18: The DT IN ACTION (Observation and Test) stage of Lean-Agile DT implementation process

In the next stage, which is **DT in action** (Figure 18), the DT functions are carried out to observe and test the DT in action before it is handed over for future use. The components and functions have been described in chapter 4.1.2. Data acquisition occurs from the physical entity from the IoT sensors and integrated into the virtual entity, where data analytics and different simulations can be performed, and the data and previously set processes can be updated. At this stage, a model maintenance team is established as well, considering the virtual entity will need continuous updates to be in sync with the physical entity. The DT in action is presented to the end-users at the end of this stage to give feedback and express if additional development is needed. In this stage, the internal stakeholders and the model maintenance team are trained by the DFTG to work with the DT.

The last stage of the Lean-Agile DT implementation process is the **Launch** stage, where everything is ready for future use. In this stage, the DFTG is out of the picture, as the internal stakeholders and the model maintenance team is capable of operating the Digital Twin on their own.

It has to be mentioned that the implementation of Digital Twin will not happen in one day; it will take time, it may take a couple of years to reach its potential, (Dooley & Camposano, 2020) mentioned in their paper that it could take 3-5 years for the DT to be a profitable, mass-market technology. As Interviewee 2 indicated, DT would slowly grow into software, and it would not be one for all problems; according to interviewee 3, DT is the future, but first other things should be considered first, for instance, digitalization of existing buildings, moreover there should be a market and customer for it. Nevertheless, the organization that wants to implement the Digital Twin concept should possess the needed resources in order to be able to maintain the DT both financially and man-hour wise.

6. DISCUSSION AND FUTURE PERSPECTIVE

This chapter is summarizes the findings of this paper as well as the future perspectives.

6.1. DISCUSSION

This chapter interprets the relevance and significance of the report's outcome and the indication of future perspective of the Digital Twin concept implementation for building operation. The key findings and relation of the literature review, analysis of the systematic literature review and interviews, and the research questions will be pointed out.

Chapter 3 reviews the background of building operation and Digital Twin to discover how Digital Twin could improve it. The research on building operation included investigating the challenges and limitations and the relations of BIM in operation and maintenance phase of the building.

The discussion of this area led to the implication of the realized benefits of BIM but lack of practical use due to technical, information and organization related issues. To summarize, these limitations are mainly the lack of guidelines on technology selection and integration, the need to improve defining the approaches to transform, store and exchange information, and the lack of LOD requirement specification. Information related challenges are related to the complexity of data; for instance, various building operation systems do not support the addition and integration of extra sensors due to its legacy format. The gathered data are never analysed and acted upon. In addition, there is a lack of understanding of the learning processes of BIM in the organization, and the stakeholders are unaware of the application of BIM technologies, protocols and processes in building operation.

The findings of the limitation of building operation led to the exploration of the Digital Twin concept, which dates back to the '70s when NASA performed simulation for the Apollo 13 mission and have been progressed ever since. The potential of the DT concept has been recognized for the entire life cycle of the product as it includes attributes such as real-time monitoring, the capability of integrating advanced technologies, like ML and/or AI, and the capability to perform data analytics and running simulations for determining different what-if scenarios.

Chapter 3.1.3 BIM in building operation has been discussed, focusing on LOD and nD BIM, which can be correlated to maturity levels of DT described in chapter 3.2.3.4, and the different types of DT described in 3.2.3.3. It could be concluded that there is a thin line between BIM and DT; also DT could be demonstrated as an advanced BIM that was developed by integrating it with additional functions, IoT sensors and advanced. BIM and DT have some familiar prerequisites about information requirements (LOD and maturity levels) and their purpose (nD BIM and different types of DT), considering that LOD and maturity levels are specifying requirements of the different stages of developments and nD BIM and the different types of DT could relate to a predefined purpose.

When developing a DT, it is crucial to specify its clear purpose to be able to provide the relevant resources, both financial and social, for its development and future use and to benefit from the variety of values fully. In general, the values of DT are real-time remote monitoring and control, greater efficiency and safety, predictive maintenance and scheduling as well as a more efficient decision support system. On the contrary, some of these values are already provided by the current building operation systems, which is why it is important to know the real reason for implementing the DT because, for the first sight, DT might seem way too complex to implement in an area where numerous systems have been developed and provide similar values as the DT. In order to determine how building operation could benefit from the potentials of DT, systematic literature review and interviews have been carried out to analyse the current status of digitalization of building operation, the components and attributes of Digital Twin in the AEC industry and eventually what values DT would provide to building operation.

Nevertheless, building operation is just a small area in the big picture where DT could be implemented, as CDBB describes the National Digital Twin where the focus is on the built environment rather than on other sectors and describes systems of systems. The systems of systems view describe the connection of complex interconnected systems where the individual systems are connected and functioning together for a greater purpose. This being said, the Digital Twin concept seems to take over the digital infrastructure at some point in the future as in the systems of systems everything is connected, DT will achieve the same where there will be an ecosystem of DTs.

This is why now the focus should be on digital asset management to be ready for future developments. The improvement of digital asset management needs to involve the connection of physical and digital assets (which considered as smart asset management) and implementing the Industry 4.0 thinking and consider the Information Value Chain (Figure 7). The Information Value Chain describes how to improve decision-making and make the data useable and give it meaning and value to generate better insight, which will help make better decisions.

Another important aspect of implementing the DT to realize its benefits, the organizations should look into “how” questions before adopting a new solution to make sure it will be valuable for them because digital technology could contribute to compelling benefits, it could cause the result of revealing dis-benefits, which at the end generate a course of unexpected problems.

6.2. FUTURE PERSPECTIVE

The future perspective of this report is to continue the further development of the Lean-Agile DT implementation process, to look into how that could be achieved technically, to establish the Digital Framework Task Group, which would consist of academic researchers who have knowledge on this area; product developers, who would contribute to set up the Digital Twin; as well as the stakeholders who would implement the DT to learn their specific needs that the current building operation system cannot accomplish. As the Lean-Agile DT implementation process describes a general process in its current stage, meaning that it needs the technological part developed, it needs the cooperation of the stakeholders (DFTG, academia and building and facility managers) is crucial.

7. CONCLUSION

The Digital Twin concept has a great variety of potential to offer to the AEC industry, that is described in this report. As described in the literature review, DT can be implemented throughout the whole life cycle of the building. In order to find in which phase DT would be more beneficial, it was recognized during the research that BIM is less implemented during the Operation and Maintenance phase of the life cycle of the building. This led to the research question *"How to enhance the implementation of Digital Twin concept in Building Operation?"* which was followed by sub-questions to help to narrow down the focus area; these sub-questions are *"What is the current status of digitization in operation and maintenance phase of the building?; What does the Digital Twin concept entail?; What value can it provide to the various stakeholders involved?"*

In the direction of answering the main research question, first, it is significant to investigate the answers to the sub-questions. The current status of digitalization in the operation and maintenance phase is discussed in chapter 4.1.1. Based on the systematic literature review, the AEC industry is slower than other industries to adopt advanced digital technologies and the implementation of BIM much further in the design and construction phase than in the operation and maintenance phase. Moreover, the potentials of BIM for building operation are recognized, but its practical use is rare, but to implement the digital technologies throughout the life cycle of the building attract attention in the AEC industry.

The components and attributes of the Digital Twin are discussed in chapter 4.1.2. Based on the systematic literature review, it can be determined that the DT has two sections, the physical end, which contains the physical entity and the user interface, and the virtual end, which contains the virtual entity, data acquisition as well as data analytics and simulations. The users can interfere with the physical end and the functions, like data acquisition from the physical entity to the virtual entity and data analytics and simulations in the virtual entity takes place in the virtual end. There is a bilateral connection between the physical and virtual entity as the DT is working dynamically, meaning that outcomes of the simulations and analyses done in the virtual entity need to be looped back into the physical entity to act upon the suggested changes.

DT's values for building operation are first discussed in the interview analysis (chapter 4.2.1), and the outcomes of the interview analysis are supplemented with the outcomes of the systematic literature review on the components and attributes of DT in chapter 4.2.2. The outcomes are visualized in the value proposition canvas (Figure 15). The values that DT can provide to building operation are enabling life cycle monitoring, smart device and advanced technology integration, data analytics and simulation to support optimal decision making. Furthermore, it is crucial to be aware of the reason and purpose of implementing the DT and advanced technologies as the values of DT would be more specific.

The Lean-Agile Digital Twin implementation process is developed, in chapter 5, to determine ways and methods to enhance the implementation of DT for building operation. This process describes an iterative approach, where the end-users are included to contribute to a flexible and adaptable process to continuously adjust the building operation needs and requirements. This process involves four stages, DEFINE where the purpose of the DT is determined, including the relevant stakeholders, the external, who are needed to develop the DT for the chosen purpose; and the internal, who is the organization would like to implement the DT. At the end of the next stages, SYSTEM DEVELOPMENT (the DT is developed) and DT IN ACTION (the DT functions are tested), the DT is presented to the internal stakeholders so that they can give feedback for improvement; also they are trained so they can operate and maintain it. In the last stage, LAUNCH, the DT is handed over for future use.

Last but not least, implement the Lean-Agile DT implementation process will happen in one day, as the DT itself need a sufficient amount of time to get to the market and be profitable, that is the reason to focus on establishing an effective way to digitalize existing buildings so that the transformation will be less complicated.

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APPENDIX

In the Appendix, the transcript of the interviews, that have been conducted as a part of answering the problem statement.

INTERVIEW 1

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

"Me, I'm the team leader of Campus Services, and my colleague is a Technician."

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

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

[…] We have an overview here and to the left we have the different areas. […]So, from the left side we have an overview of all of our ventilation systems, and right next to that we have all our heating systems, and next to that we have the hot water systems, and the next step we can see an overview on each floor, so when clicking on one of the floors you have an overview of the specific floor that you want to see.

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

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

And all these data are real-time data right now?

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

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

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

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

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

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

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

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

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

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

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

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

"Yes, well if I understand your question correctly, we don't have within the building management system an energy overview because it's too expensive to buy it with this company. So, we have a separate energy systems where all the data is and there we receive all the energy values, so we can see for instance this building compared to another building is it producing or is it consuming more electricity or less and also per square meters, so it's easier to compare the two buildings and then we can see there's a high level of energy. We can also get an alarm if we see a quick rise in water consumption etc. We can see that but that is a separate system. We have about, I think between 1200 and maybe 1500 energy measures, so we have a lot of data."

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

INTERVIEW 2

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

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

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

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

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

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

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

"Yes, they do all the things there but by themselves. We never type in any data into their system they do it by themselves, but we have a lot of customer requests. So, for example we have a booking

system so we can see which, if we have somebody who rents hotels so you can imagine you have a 3D building, probably a Revit model or something like that, and you upload it to our system and we have all the rooms inside. And when they book a room, because the normal system they have it's just a list of all the rooms they have, but they want to see, they want to combine our, is this room booked? when did we last have the cleaning here? when is it booked.? So, we do some of these integrations and link them together, so they can add both their, if they use QR codes in these rooms, how are they linked to the booking system, and how is that link to their cleaning and general facility management, which kind of assets do we have inside of this room, which kind of TV, what type of channels do we have on that TV. And we can continue and continue to add this data, but we have a placeholder where we can link all of this together."

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

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

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

"Even though you call it live data, it is always set up like this, so it's always set up to be when something new it pushes data into the system, so it is live data even though it's by an interval, but it's called live data. So, if you have the IoT, some kind of sensors for all different kinds of, even though we use geometry, we split it up in My current company, even though we have geometry is just a placeholder, it's just a placeholder where you link this data together. If you use the actual geometry it doesn't have to be in […] that's just one part of all the data that you have. So, geometry is actually a stupid thing to link it to, because it always changes. So, we have done it a bit different in our system, so we have something called assets, because we also cover things that are not a part of geometry, so you don't want to, you don't need an object, a geometrical object for example a television, you need to place some data on this part, you don't need it visualized in 3D, you only need a placeholder, you only need somewhere we can link all this data together. And that's how we try to do it, so if you link 3D geometry to it that's just one part of it, but then you have all the rest and that's how we see this, because you don't need to visualize it in 3D, somethings you do but not all. So, the room is also, you can say even though it's it has some geometry it doesn't need that, it's maybe restricted by some rules, by you can say by walls and ceilings and stuff like that, but you can also have areas. Areas is something different than for example a room. So, it's just to explain how we see this IoT, you select the sensor, could be heating, could be something and you

select the way you want to visualize this, in this case if it was heating, would probably be the room, but if you have one sensor or multiple rooms then you would probably combine this and stuff like, but it would be a property connected to the room maybe, in our system or something else."

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

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

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

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

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

"Who is the user?"

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

"I would say that depending on who is the user, I think the perspective is very different, but that would be my take on it. We create software, we see a lot of use cases, but it's very different what the use case are, and it's very difficult if we don't have for each like IoT […] that can be so many things. So depending on if we don't focus on one part of it, it is very difficult to say what is the value of it, because it depends so much on who are the user of it and what do we want to use it for. It's very difficult if you don't know the end goal and the values of it when we start these projects. We just made integration with client that they have bought our system and they have vacation houses, that they rent out for people and I think they have 300 of those or something like that. It was very difficult for them to see "I need to go there, and I don't know, fix the door, and it was very difficult for them to see, to plan their work day if they didn't have, is there other people in it, is the vacation home booked or not. And that comes from their booking system, and we don't have a booking system in our system. That's a small integration but you can add on to this depending on the use case, and it could also be all the small things and we can […] Internet of Things, is also

some people use drones, they scan their buildings and then they update it directly. It's also not a live coverage but a day-to-day coverage of building portfolio. How much value does it give? It's very hard to say, but it's depending on which portfolio you have. It's very hard to say in such broad terms what is the value because each one of these is its own use case, so I think that would be my take on it. If you look at BMS systems it's pretty much the same. They cover some things and the same, we can show data inside of our system. What is the value of it? You don't need to log in to two systems. Normally that would be the value of it, so depending on you can link it to your 3D geometry, maybe some of it, because it's different data, but it depends on how you like to use it and how much you use it I guess."

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

INTERVIEW 3

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

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

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

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

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

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

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

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

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

“I don’t think I understood the questions.”

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

“Yes.”

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

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

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

“If you by that you mean sensors and stuff, do you mean that?”

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

“I think it’s the future, because the complexity of this data is increasing dramatically and it is easier for a human beings to identify objects by looking at it in 3D then looking at lists and mobile applications and so on, so just the identification of the building, which building this is, and for example I had a customer yesterday, who asked me about the 3D modes, “can I go into this specific room and measure the height of these windows” and I did that and he said oh that saved me from a trip of 10-15 kilometres. So if you have this kind of data digitized that way you turn complex data into a visualization that human beings can easily understand. So this is this is again the future, and we have some customers with object 15,000 building models in the FM system so I mean, something that is often overseen is the maintenance of these building models. You have to have a governance policy process to maintain these data, and this is probably one of the hurdles, so if you were as a building owner what this level of degree, you have to be clear that you need the

manpower to maintenance or the money to maintain it. So I think in the municipality of Copenhagen they have around 5,000 Revit models to the buildings and they have six employees, that's doing nothing but the maintenance of this, and this is only used for space management, so I mean this is the future but I think that this is, in order to maintain any data on an object level this is highly time consuming and this needs to be decentralized to all the people that don't work with drawings on a daily basis.'

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

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

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

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