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Facilitating Facility Management By Using Digital Twin

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Project Management
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Abstract

This master thesis is done based on literature review and interviews with some experts in the sector. The goal of this study was to close the gap between theory and practice regarding Digital Twin application for Facility Management (FM). Very advanced Digital Twin conceptual frameworks are available in theory, but in practice, it is not very common.

To meet the goal of this study, three research questions were formulated. The first and the main Research Question, which is thesis title as well, (1) How to facilitate FM using Digital Twin? To answer this question, benefits, and challenges of that needed investigation. That brought up second and third research questions. (2) What are the benefits of Digital Twin in the sector.

To answer research questions, a mixed literature review method is conducted in the first step. Regarding Digital Twin and FM more than 1000 articles were found. Analyse on keywords and related topics were done by using VOSviewer software. Most relevant topics were introduced in theory section. Then, in second step a qualitative interview process is done with 10 experts in the Architectural Engineering and Construction (AEC) sector. Empirical results were presented in forth section of this thesis. Finally, both theory information and empirical results were discussed and analysed together.

The conclusion of this thesis can be abstracted in two messages. First message is implementation of Digital Twin in the sector is highly entwined with concept of Digital Transformation. This idea is totally missing in literature and has been taken from analysing empirical results. Digitalisation is considered with Digital Twin, based on literature analyses by VOSviewer software, but Digital Transformation is a missing part that hopefully investigates more in future. Second message, conclusion, is FM-tools are important part of implementing Digital Twin in sector with purpose of FM. FM-tools are not well investigated in integration with Digital Twin.

Preface

Using Digital Technologies are getting more and more attention in order to facilitate different activities in the real world. Digital Twin is an emerging concept that has potential benefits for different sectors. Architectural Engineering and Construction (AEC) sector seems to be an important sector where Digital Twin concept is not well developed yet. Although some advanced conceptual frameworks were published recent years, I thought there should be some missing ideas that need to be considered while developing theories.

Facility Management (FM) plays an important role in AEC sector, where Research and Development (R&D) in this sector is not as substantial as R&D in other sectors like Information and Communication Technology (ICT). People in AEC sector are less familiar with new technologies and continue their routines as they were doing over decades. While Operation and Maintenance (O&M) phase of projects lasts over decades, minor advancements also can have huge impact. Circular Economy (CE) and Sustainable Developments are hot topics that are getting more and more attention while environmental changes like global warming arise.

I want to express my sincere gratitude to my supervisor Nora Johanne Klungseth for her insightful discussions and feedback, as well as for guiding me in correct direction. She also assisted me in looking for suitable interview objects that I needed for my research. She supported me through this research study during last year. Specialization project, 15 credits, that I had in third semester and my master’s thesis, 30 credits, in forth semester, Spring 2022.

Additionally, I want to express my gratitude to the individuals from different organizations that participated in my research through interviews. They gave me better insight into this study subject. I got necessary data to carry out my thesis in the direction I thought would be beneficial.

Finally, I'd like to express my appreciation to NTNU's Department of Mechanical and Industrial Engineering (MTP) and Norwegian Centre for Research Data (NSD) for allowing me to conduct this research study for my master's thesis. Also, NTNU gave me access to almost all literatures I needed through its library search engine “Oria”.

Navid Elyasi

Trondheim, Norway, June 2022

Abbreviations

CE – Circular Economy
AEC – Architectural Engineering and Construction
IoT – Internet of Things
AI – Artificial Intelligence
AR – Augmented Reality
VR – Virtual Reality
ML – Machine Learning
CPS – Cyber Physical Systems
ICT – Information and Communication Technology
DT – Digital Technology
NSD – Norsk Senter for Forskningsdata
O&M – Operation and Maintenance
R&D – Research and Development
FM – Facility Management
BIM – Building Information Model

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1. Introduction

Computerisation and digitisation playing underlying role in Industry 4.0. Using Digital Technology (DT) gets more attention of many scholars now. Even Digital Technologies and industrial revolution can lead to a great improvement in Circular Economy (CE) (Laskurain-Iturbe, et al., 2021). The world has made a new record of 100 billion tones material consumption where only 8.6% of that recycles and gets back into economy (Circularity Gap Report, 2020). CE's primary principle is to achieve long-term growth by making the best use of available resources while reducing waste and emissions (Laskurain-Iturbe, et al., 2021).

One of the strategies that assists industries in achieving the CE target is maintenance. Linking Digital Technologies with Facility Management (FM) is chosen for this thesis. Digital Twin is selected as a Digital Technology, that is growing in different sectors during last decade. Alarcón, M., et al. (2021) successfully cut near 50% of energy consumption in a real case of and international organization by efficient Operation and Maintenance (O&M) practices.

Using different technologies in Industry 4.0 are discussed broadly. DTs such as Internet of Things (IoT), Virtual Reality (VR), Augmented Reality (AR), Building Information Model (BIM), Digital Twin (in this thesis, the abbreviation DT is only used for Digital Twins because it is more widely used in the literature), Cyber-Physical Systems (CPS), 3D Printers, Blockchains and most importantly Artificial Intelligence (AI) (Marsden, P., 2019). According to Burke, R., et al., (2021, p38) all the aforementioned technologies, as well as Project Management (PM), are transforming our economy and lives. Data, as previously established, is critical in industry 4.0. When we talk about data, we're talking about gathering information, transferring it, and translating it into knowledge and wisdom, as well as making better decisions.

Marsden, P., (2019) studied Industry 4.0 and digital transformation process through different DTs. They say: "*Digital Technologies have arrived and are here",* and advantages of DTs need time to well understood in the market. Dzulkifli, N., et al. (2021) presents IoT, BIM, VR/AR, and Computerized Maintenance Management System (CMMS) as the main technologies which have great impact on Architectural Engineering and Construction (AEC) industry. Lu, Q., et al. (2022) mentions CMMS, Computer-aided Facility Management (CAFM) systems, Building Automation System (BAS), and Integrated Workplace Management System as the main FM tools in AEC industry. But still, FM requires a great effort, time and energy and the most important problem is information management in these systems.

1.1. IoT, an essential element in Digital Twins

IoT is one of the main elements of Digitalization as it contributes to collecting and transferring data within different industries. IoT sensors can improve data sharing and data utilization, which results in lower costs. IoT sensors can play an important role to data handling, collection, sharing and even storing data in the cloud systems. Lu, Q., et al. (2022) says "Achieving a comfortable living environment and smart building management is a complex issue in O&M, which costs around 80% of whole life-cycle cost.". Errandonea, I., et al., 2020, says sensors and intelligent data usage are affecting and improving the whole lifecycle of assets. They mention sensors and data being collected can be beneficial in designing and recycling as well as O&M.

Various IoT applications in the literature review have found. For example, Tavana, M., et al. (2020) presents an Enterprise Resource Planning (ERP) based on IoT. Cheng, J.C.P., et al. (2020) presents BIM based on IoT sensors to achieve preventive maintenance. Other scholars like Yu, G., et al. (2021) worked on Digital Twin for the purpose of O&M in tunnels, Lu, Q. (2022) worked on technologies in O&M of buildings, Sivalingam, K., et al. (2018) worked on Digital Twin to maintain Wind Turbines.

One of the latest literature reviews related to Digital Twin and maintenance were done by Errandonea, I., et al. (2020). They've demonstrated the growing interest in Digital Twins and Maintenance in the literature, see figure 1-1.

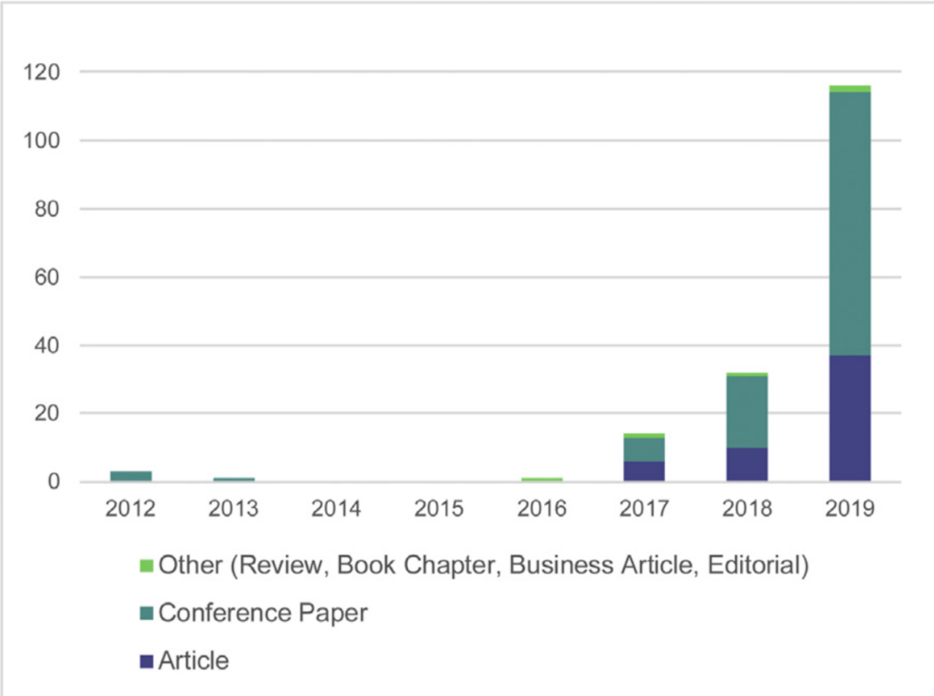


Figure 1-1: search results regarding to Digital Twins and Maintenance (Errandonea, I., et al., 2020)

A Preventive Maintenance framework based on BIM is presented by Cheng, J.C.P., et al. (2020) that uses IoT sensors as the main component in their study. Underlying role of data can be found in definition of both BIM (Eastman, C.M., et al., 2011) and Digital Twins (Scheper, T., 2021). Standardization is an important factor when it goes to data usage in a system. Development of both concepts, BIM and Digital Twin, different standards for data structure and data transformation are presented (BuildingSMART[1]; NBIMS-US[2]; BS 1192-4[3]; Yu, G., et al., 2021).

IoT sensors are a great tool to deal with data collection and data integration. when searching IoT keyword in articles, a huge number of different IoT applications can be found. When year of publication being considered, increasing trend of IoT applications is realized, i.e., searching through "Sciencedirect" with IoT as the Key Word gives 663, 2053, 4570, 8049 articles for the years 2015, 2017, 2019, 2021 respectively.

[1] https://www.buildingsmart.org/
[2] https://www.nationalbimstandard.org/
[3] https://www.designingbuildings.co.uk/

Through past decade IoT sensors became more and more powerful, reliable, and durable with lower prices (Burke, R., 2021). IoT sensors enable us to collect data even in dangerous situations or situations that human is unable to go and manually collect data. That is a critical reason for growing rate of IoT applications in industry. Projects and factories can get more and more data that leads to many advantages within system. So, IoT plays a fundamental role in the Digitization, Digitalization and Digital Transformation. Tavana, M., et al., (2020) investigated potential challenges, unsolved issues, and new applications of IoT-based systems.

Many challenges and applications of IoT are investigating via scholars, specially in "Internet of Things" journal. But within this thesis the main concern is more general regarding application and challenges of Digital Twin. Digital Twin seems to be presented by scholars more than 20 years now, but still struggling to find its path to practice.

1.2. Facility Management (FM) and Its Importance

Zhao, J., et al. (2022) says technological advancement in software, hardware, and applications during last years has dramatically changed the way AEC sector manages its projects. Specially building assets throughout their lifecycle, with a focus on automating FM processes to boost job efficiency during the O&M phase. Zhao, J., et al. (2022) say "The O&M phase has received considerable attention compared to other phases over the years since it accounts for circa 80% of the building whole lifecycle cost and is considered about 15–25 times more than the design and construction phases". Actually it could be different for buildings with different purposes. For office buildings it could be more than 66% of annual cost or between 25% to 50% for private buildings (Bjørberg, S., et al., 2005).

The literature study by Errandonea, I., et al. (2020), which appears to be the sole review of both Maintenance and Digital Twins (as a Digital Technology), provides us with a clear picture of Maintenance's technological obstacles. When two conclusions of Errandonea, I., et al. (2020) are considered together, as shown in both charts in figure 1-2, the potential and benefits of digitalization in the AEC industry become clear. The figure on the right demonstrates that Digital Twins have a lot of potential in the "Maintenance" area, whereas the chart on the left shows that they aren't employed much in the "Construction" and "Logistic Services" areas.

Kristoffersen, E., 2021, in page 2 of his thesis, as the main purpose of his PhD study says: "the question of *"in what areas" and "in what ways" Digital Technologies supports the implementation of Circular strategies for companies have been insufficiently researched"*. So, the main concern of this thesis is "in what areas" and "in which ways" Digital Twin can help and support FM in AEC and building.

Advanced technologies are getting more attention during last decade, and it's mentioned by NIC, (2017) that AI will add 10% to IK economy by 2030. On the other hand, many scholars considered using DT for the purpose of FM. A multi-level Digital Twin is presented by Cheng, J.C.P., et al. (2020) with the purpose of preventive maintenance with power of Artificial Intelligence (AI). They used IoT and BIM in the first layer, information layer, to collect data. After that they used Machine Learning (ML) algorithms, in second layer, to make preventive maintenance happen. Gbadamosi, A.Q., et al. (2021), used IoT sensors with the purpose of real-time monitoring and ML algorithms to have preventive maintenance.

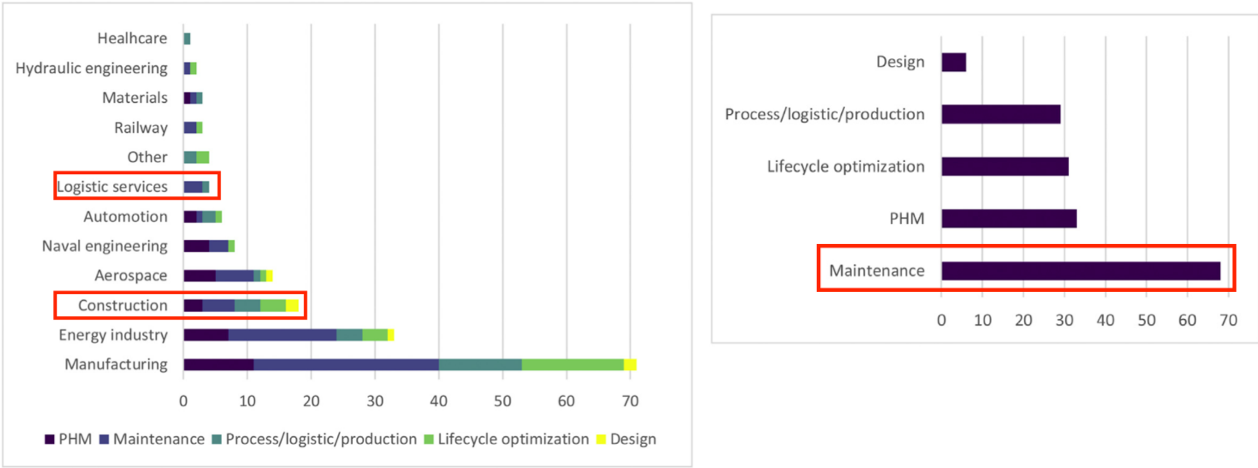


Figure 1-2: Digital Twins in industries (left chart) and its applications (right chart) (Errandonea, I., et al., 2020)

CE's main purposes, sustainability by optimizing use of resources is totally aligned with FM purposes (Laskurain-Iturbe, et al., 2021). From Kristoffersen, E., (2021, p.2) perspective, "*CE includes a range of circular strategies and business processes: from recycling to reuse and designing new offerings to managing maintenance.*". From both viewpoints, FM can have positive effect on CE.

Benefits of CE in different areas are broadly discussed by scholars, but still roadmap for that to happen is challenging (Kristoffersen, E., 2021). Laskurain-Iturbe, et al. (2021) mentions huge positive influence of DTs of Industry 4.0 on CE, as the main result of their study. *"These improvements are mainly related to reduce material and energy consumption, and waste and emissions generation."* This is still a debatable issue, how Digital Technologies of industry 4.0 can assist in better O&M to enhance circularity in practice.

1.3. Research Targets

Finally, the main Research Questions (RQs) that this research is anchored on are:

RQ1: How to Facilitate Facility Management using Digital Twin?

RQ2: What are the benefits of using Digital Twin for FM?

RQ3: What are the challenges of Digital Twin in the sector?

1.4. Out of Scope

In this study on the first step of literature review, VOSViewer software is used to analyse related keywords to Digital Twin and depict a good picture of relevant and irrelevant topics. Some relevant topics are described in theory section because we needed to discuss later in this thesis. But still some out-of-scope topics are:

1- Cyber Physical System (CPS) is very similar to Digital Twin and is miss interpreted in some literatures. The main difference between CPS and Digital Twin is CPS **combines** physical and computer or cyber components. While Digital Twin **connects** physical and Digital component together. Physical component is something that exist in nature, something biological entirely or something that is developed by human. In Digital Twin world, a digital copy of that is created in cyber / computer world and connected to physical object. But in CPS, computer / cyber components are included into physical object (Rawat, D.B., et al., 2015).

2- Machine Learning (ML), Big Data and Artificial Intelligence (AI): These two technologies are very close to Digital Twin, and we found them as part of some studies on advance version of Digital Twin. But the goal of this study is practical applications of Digital Twin. Basic version of Digital Twin still struggling to be involved in real world of business. So, these two concepts are put to out of scope of this thesis while we need to keep in mind that for advanced Digital Twin we need to consider both of them.

3- Drones and 3D-Printer: these two are more relevant to graphical and visualization aspects of technologies (Marsden, P., 2019). both can be beneficial for Digital Twin in Design and Construction phases of projects

Another topic that needs to be discussed more clear here, in this subsection is CE. Circular Economy (CE) is a broad area of study. It has a wide range of aspects in different industries. Based on their relevance to this research study, these features can be divided into two categories. These two groups are later provided in figure 4.6, by numbers on Kristoffersen's framework, in the conclusion section (2021). These are the two groups:

1- Directly related: features like reuse (materials, parts and products), recover, restore and refurbish are raised by some scholars (Kristoffersen, E., 2021; and Laskurain-Iturbe et al., 2021) that are relevant to this thesis.

2- Indirectly related: Other considerations include the repercussions of previous elements as well as longer-term accomplishments. Rethink/redesign, reconfigure business model, recycle products/materials, minimize wastes and emissions, additive manufacturing, Big Data and Advance Analysis, Business Analytics (BA), and Circular-Oriented Innovation are all topics that are tangentially related to this study (COI). These tangential features of CE are similarly out of bounds.

1.5. Structure of Report

This master thesis consists of 7 sections. Introduction, theory, methodology and research approach, empirical results, discussion, conclusion, and future path. This current section, introduction is an overview of Digital Technologies, especially Digital Twin and their relationship with FM, as well as importance of FM in the sector. Then research questions and research scope are presented. Next section, Theory Section, includes theoretical background of related concepts, like FM, BIM, CE, Digital Twin, CE, and available frameworks in this subject. FM and Digital Twin as the main concepts are presented and discussed more in that section. Some other topics like BIM, CE, CPS, VR and AR are close to Digital Twin and can be related to this thesis, thus introduced briefly in section 2, theory section. Third section, Methodology and Research Approach, describes research process of how literature articles are selected and how interview objects are selected. Section 3, also, presents interview process, privacy, ethical considerations, validity, and reliability of interviews. Section 4 is empirical results; outputs of interviews are presented in that section. Section 5, discussion section, interview outcomes are discussed with comparing to theory section from literature. By comparison of interview results and literature review results some conclusions are presented in Section 6. Section 7, future path, presents research gaps that have been found in this thesis, that can be used for later studies.

2. Theories

In this section, related concepts and definitions are discussed. Firstly, a literature review is done related to the research topic, Facility Management (FM), and it is presented in section 2.1. Then, topics and keywords close to Digital Twin are presented in section 2.2. in section 2.3, Digital Twin is presented and later, in section 2.4 combination of both concepts, Digital Twin in the purpose of FM are presented.

1.1. Facility Management (FM)

2.1.1. Introduction of FM

International Facility Management Association (IFMA) defines FM as "*A profession that encompass multiple disciplines to ensure facility of the built environment by integrating people, place, process and technology*." A general definition of FM is also presented by Ebinger, M., and Madritsch, T., (2012) that suggests including FM in a Built Environmental Management Model (BEM2). This idea of having built information for facilitating FM is suggested by different scholars like Kassem, M., et al (2015) and Jang R., et al (2020). Atkin, B., 2015, p.3, states no universal definition for FM can be found, FM suggested to be dependent on Organizational needs, and it could be different for different sectors. Thus, based on the purpose of this research study, Architectural Engineering and Construction (AEC) sectors' need are considered more related to FM methods and approaches.

Atkin, B., (2015, p.17) states FM as a broad management area including Organizational Management, Financial Management, Innovation and Change Management and Human Resource Management. Actually, FM is potential to enhance whole system's performance, although bad FM has negative affect to all systems and subsystems.

Organization in a holistic view considers FM in different steps. Start with Design, construction, test and commission, start-up and finally operation (Atkin, B., 2015). This is presented in figure 2-1. In this research study focus is on the operation step.

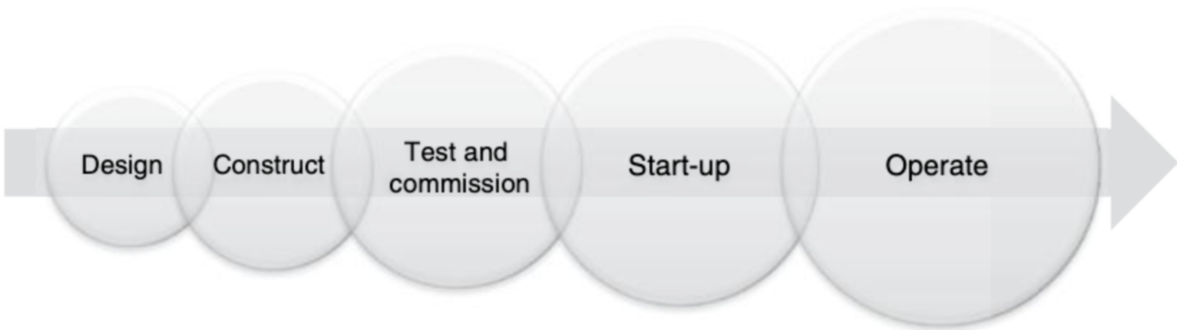


Figure 2-1: Facility Management phases (Atkin,B., 2015)

2.1.2. FM in Operation and Maintenance (O&M)

As discussed in section 1.2., Facility Management and Its Importance, of introduction, this study focuses on operation phase of buildings. In operation phase, Operation and Maintenance

(O&M) two main strategies are available, planned, and unplanned maintenance. Unplanned maintenance is known as corrective or reactive maintenance. This type of maintenance is suitable only for assets that don't have big impact on business. The other type of strategy that is planned maintenance is more suitable in real practice. Figure 2-2 shows different strategies of maintenance.

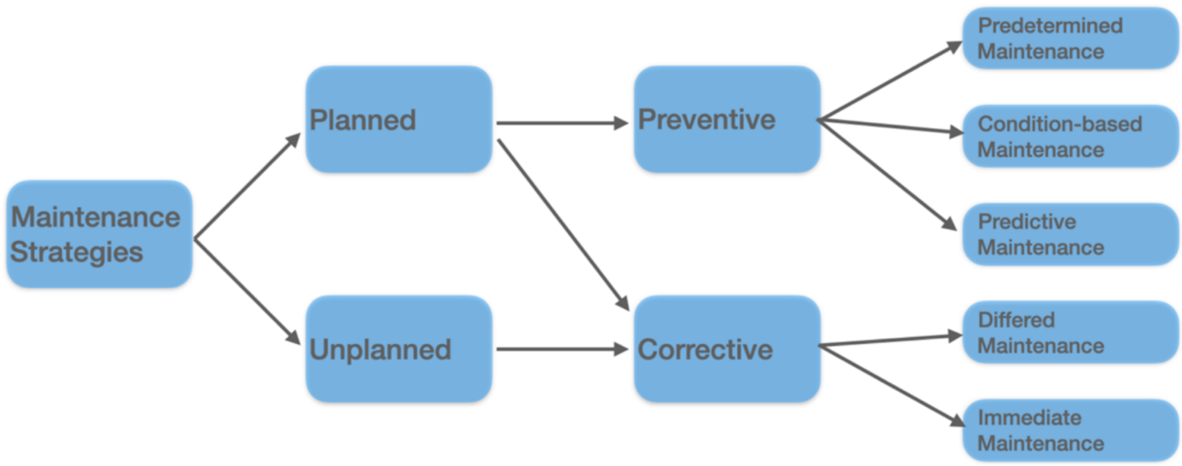


Figure 2-2: maintenance strategies (Atkin, B., 2015)

Preventive maintenance categories are much more efficient for FM. Preventive maintenance has different categories, and the most basic version of this category is routine maintenance that some scholars named it as predetermined maintenance. This type of maintenance is based on experience of prior assets. This is not the best preventive maintenance but still much better than corrective maintenance (Errandonea, I., et al, 2020).

Two other types of preventive maintenance are Condition-based maintenance and predictive maintenance, which are more efficient in practice. Condition based maintenance is based on observation or getting data from asset (Nikolaev, S., et al., 2019). This type of maintenance is increasing due to technology growth specially in IoT sensors. Even artificial intelligence has recently enhanced this type of diagnosis maintenance (Mabkhot, M.M., et al., 2018).

Predictive maintenance is another strategy of preventive maintenance that has gained more attention during recent years with growth of technology. There are two main types of this strategy, data-driven or model-driven approaches (Zenisek, J., et al., 2019). Data driven approaches need big data. For example, Liu et al., (2018) uses a data fusion algorithm combined with Digital Twin to perform predictive maintenance. On the other hand, model driven approaches are usually based on mathematical calculations. Making these models is not very simple, but they are very accurate and trustable (Errandonea, I., et al, 2020).

2.1.3. FM and Digital Technologies

Dzulkifli, N., et al., (2021) describe four effective technologies for the AEC industries in one of the most recent literature reviews that is found. These four technologies, as well as their applications, are shown in Table 2-1. This table lists all the features that will be addressed in the proposed solution. The features described for CMMS and VR/AR are the same features mentioned in other works of literature for Building Information Model (BIM) (Cheng, J.C.P., et al., 2020) and Digital Twins (Rabah et al. ,2018; Sivalingam, K., et al., 2018; Errandonea, I., et al., 2020).

Table 2-1: Digital Technologies and their features in industry (Dzulkifli, N., et al., 2021)

Technology	Features
Computerized Maintenance Management System (CMMS)	• Replace conventional method • Easily assign the work order to technician and team • Technician get notified of work (location, assets, and parts) faster • Building users can create work request and able to track down the status • CMMS can track the entire life cycle of an asset • Can be used in mobile app • Available in cloud-CMMS
Building Information Modeling (BIM)	• Improve productivity, efficiency, and time. and cost-saving • Provide centralized and rich information store to facilitate data retrieval and transfer between different ICT systems • Able to reduce the manual processing of information handover, increasing the accuracy of data, and improve accessibility to this data
Virtual reality (VR) and Augmented reality (AR)	• Minimize travel • Reduce risk for technician • Support maintenance • A better understanding of facility needs and visual asset information in real-time • Train workers
Internet of Things (IoT) sensors	• Via predictive and preventive measures • Improve quality and amount gather data • Quick maintenance decision and based on real-time information • Promote integrated product and service operations • Analyze common failure mode and fixing equipment before failure

The first technology that is mentioned by many scholars, Lu, Q. et al. (2022) and Ghorbani, Z., et al. (2022), is CMMS. CMMS allows companies to manage all elements of maintenance in a systematic application. Having all information about all assets in a system, all workflows linked to those assets, and a record of maintenance activities, operators, and the maintenance responsible team for each asset are some of these characteristics. Above all, a key aspect of a CMMS is the ability to create various/customized tables and diagrams to making comparison for managers to better understand and make choices (Lu, Q., 2022).

Another technology is BIM, which improves the efficiency of maintenance activities while also increasing data accuracy. More information on this technology can be found in Section 2.2.1, BIM. The third technology is virtual reality (VR/AR), which focuses on data visualization. These technologies lead to a significant understanding of both the asset and the ecosystem, as well as efficient training capabilities (Zheng, Y., et al., 2019). Virtual reality and augmented reality are closely related to Digital Twin and are discussed in this section. The Internet of Things (IoT) is the most important technology for CMMS, BIM, Digital Twins, AR, and VR (Eschena, H., et al., 2018).

Alarcón, M., et al. (2021) offer a coupled Energy Management System (EMS) and Maintenance Management System (MMS) that would be capable of interacting with Enterprise Resource Planning (ERP). They installed the system in a global corporation in Murcia, Spain, and found 50% reduction in energy use as well as improved maintenance performance. They utilized ultrasound IoT sensors in boilers, for example, to detect and predict leaking. “The information collected through both systems has become key element in the company decision making process.” In this sentence, they are referring to data collecting in EMS and MMS systems.

Gbadamosi, A.Q., et al., 2021, offer an IoT deployment approach for the Rail Asset Maintenance sector. They began by looking into asset maintenance issues in the train system before proposing their model. They run a series of workshops with various groups of industry experts to identify the most pressing issues and develop IoT-based solutions. Their idea comprises a data management system, real-time monitoring, remote inspection, and, on top of it all, preventive maintenance using machine learning algorithms.

2.2. Keywords close to Digital Twin

By searching around Digital Twin, some technologies or concepts are considered to have overlap with Digital Twin. Based on definitions and capabilities that have been found for Digital Twin, it is required first to go through those concepts to some extend to make a better discussion around the topic.

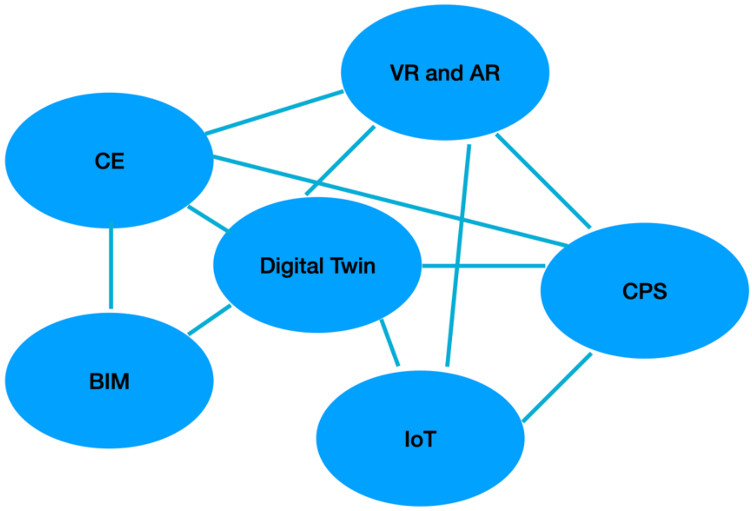


Figure 2-3: Concepts close to Digital Twin (Own Creation)

2.2.1. Building Information Model (BIM)

"*Information is Lifeblood of Facility Management; without it, the organization is not in control of its facility assets and is unlikely to be able to account for them reliably.*" (Atkin, B., 2015). BIM was first introduced as Building Product Modelling (Eastman, C.M., et al., 1999) or Building Data Modelling (Penttilä, H., 2006) to manage information digitally. It later evolved into a more structured concept by Eastman, C.M., et al. (2011), which presents a digital modelling technology to represent buildings and building components with attributes and parameters for construction, analysis, and communication. Furthermore, (Marsden, P., 2019, p.69) refers to BIM as the best practice for synchronizing all information throughout the Environmental Management Plan (EMP) and ensuring that there are no information gaps or duplications in the system.

Parsanezhad, P., (2019) claims that BIM is a gamechanger in the AEC industry. Traditional as-built information, as well as dynamic/real-time models, are transformed into a digital version that can be updated more readily using BIM. However, most technicians believe BIM is a static record, similar to traditional as-built documents. Ding, L., and Drogemuller, R., (2019) claim that BIM can reduce updating time of databases by 98%, or reduction in information loss is claimed by (Lu, Q., et al, 2018).

Lu, Q., et al., (2022) wrote an article with the title: "Moving from building information models to digital twins for operation and maintenance". In this article they present a comprehensive review about BIM and Digital Twin about FM in AEC industry. And they suggested BIM weaknesses and reasons industry needs to move forward to Digital Twin.

2.2.1.1. BIM Framework

There are various BIM frameworks in the literature review. BIM framework produced by Succar, B., et al., (2015) is one of the most suited versions of BIM framework based on Parsanezhad, P., (2019). It comprises three primary axes, each of which includes more details. BIM phases, fields, and lenses are the three axes. This structure is depicted in Figure 2-4 below.

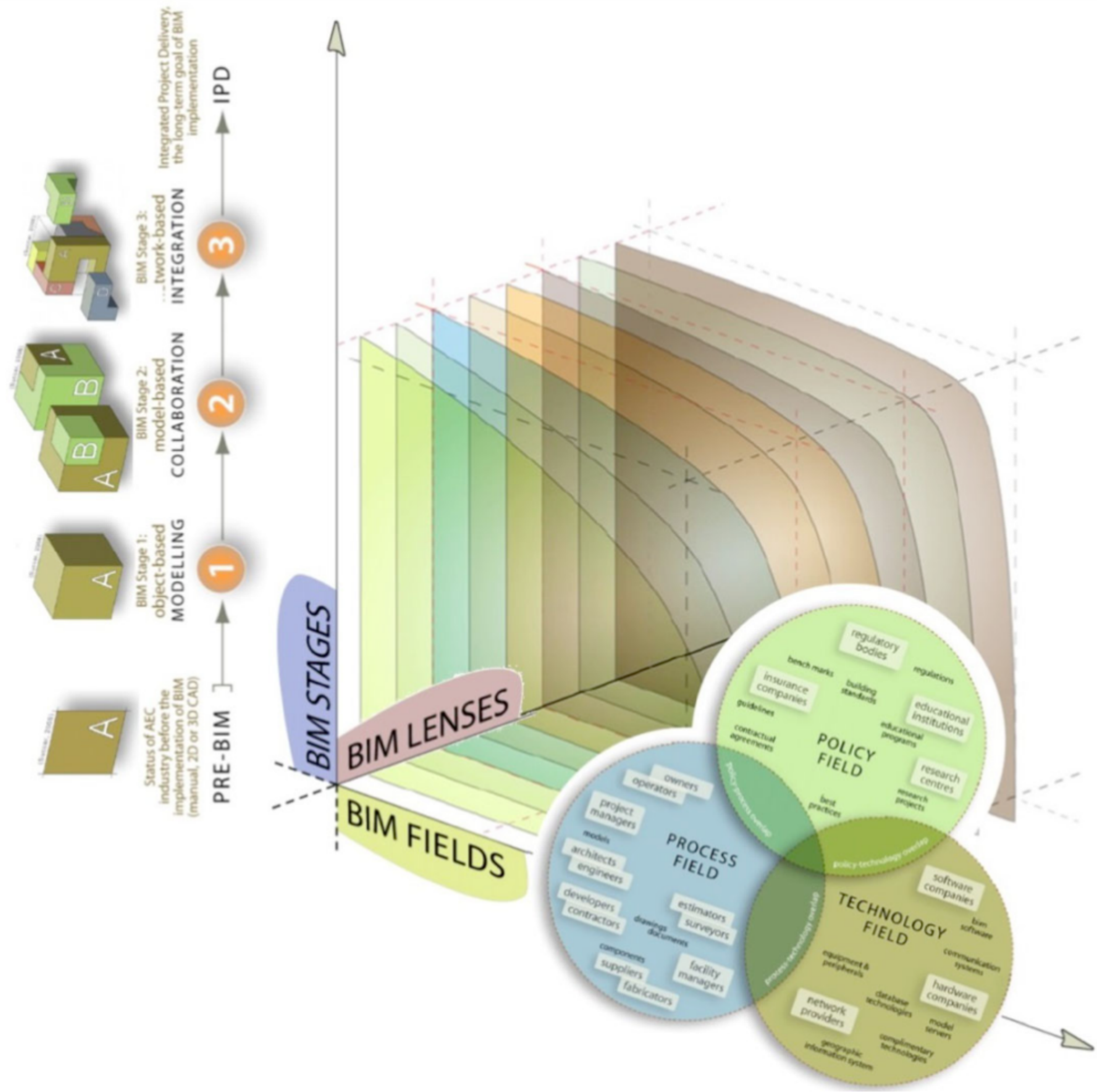


Figure 2-4: BIM Framework (Succar, B., et al., 2015)

Axis 1- BIM Fields, three separate fields are shown on this axis:

1- Policy field: regulatory bodies, insurance firms, educational institutions, research institutes, regulations, contracts, standards, instructional programs, and research projects all fall into this category.
2- Process field: Facility managers, project managers, engineers, and architects, as well as the information they consume and produce, are included.
3- Technology field: This comprises communication systems, model servers, and databases, as well as software, hardware, and network providers.

Axis 2- BIM Stages, this axis has five stages:

1- Pre-BIM: Traditional as-built paperwork and 2D drawings created with CAD software are used at this stage.
2- Object-based modelling: The minimum requirement for a BIM environment is 3D object-based models.

3- Model-based collaboration: a model-based BIM is created by combining several object models.
4- Network-based integration: Putting in a core server and database, as well as merging several components into a centralized system.
5- Integrated Project Delivery (IPD): This is BIM's long-term ambition, which integrates BIM throughout the construction phase and allows businesses to optimize construction processes through limitless simulation iterations.

Axis 3- BIM lenses, this axis has three levels, ranging from a broad overview to a more thorough look:
1- A macroscopic lens: at the industry level, a very high-level view.
2- A mesoscopic lens: Inter-organizational perspectives are included in the middle view.
3- A microscopic lens: in each level, there are more details.

Cheng, J.C.P., et al. (2020) present a BIM- and IoT-based data-driven preventative maintenance framework for preventive maintenance. There are two layers to their framework. (1) Information Layer: BIM, IoT sensors, and the Maintenance Database are all part of this layer. (2) Application Layer: This layer contains modules such as condition monitoring and fault alarming, condition assessment, condition prediction, and maintenance planning. They apply machine learning techniques in the maintenance planning module of the application layer to estimate required maintenance and plan the most viable maintenance tasks.

BIM in many literatures is mentioned as a tool to facilitate FM. Lu, Q., et al., (2022) mentions bellow items, see table 2-2, as the main contributions of BIM to FM.

Table 2-2: BIM contributions to FM, Lu, Q., et al., (2022)

BIM Key Contributions to FM
Accurate and efficient support for decision-making, monitoring and communication
Easy retrieval and storage of maintenance, inventory, warranty, installation and operation data
Enhanced collaboration and increased visualisation for stakeholders
Effective management and planning of orders, activities, schedules, labour and space
Convenient maintenance and tracking of assets
Optimised use of fuel, utilities and materials
Facilitation of emergency evacuation planning

2.2.2. Cyber Physical System (CPS)

When investigating the history of Digital Twin, the concept of Cyber-Physical Systems (CPS) is also worth mentioning, because there are many similarities in these two concepts. According to Lee, E.A., et al. (2008), a CPS is a combination of computational and physical processes. However, when the name Digital Twin was investigated, Lee, J., et al., (2013) utilized CPS as a synonym for Digital Twin because it replicates an object's health using both analytic techniques and physical knowledge. Rawat, D.B., et al., (2015) describe CPS-based manufacturing as a revolution for industry 4.0 because it offers each physical entity with a virtual representation that can be Digital Twin, but he didn’t mention Digital Twin in their study. In their model storage space, sensors, actuators, and named digital object memory play important role to create a virtual representative and virtual combined objects.

The various CPSs can communicate and exchange information with one another, as well as initiate activities and control one another interactively. Although Rewat, D.B., et al., (2015) does not use the term "digital Twin" in the text, his description is remarkably like what other scholars are mentioned about Digital Twin.

The main difference between CPS and Digital Twin can be found in their definitions. CPS combines physical world with cyber / computer world, but Digital Twin connect physical world to digital world. The main element of Digital Twin is to create a digital replica of real object, while this is not a main idea of CPS. For example, a robot can be made as a CPS without having a digital replica in computer world.

Sabeur, Z., et al., (2021) presents an advanced CPS which is based on Digital Twins. But to keep focus on main research questions and avoid extra complexity, CPS is not included in this study.

2.2.3. Virtual Reality (VR) and Augmented Reality (AR):

IoT and Digital Twins will play essential roles in large data, complex systems with multiple interconnected subsystems, and automation (Scheper, T., 2021). Firstly, two key technologies: Virtual Reality (VR) and Augmented Reality (AR) should be defined and separated. VR is a digitally constructed world, object, or environment that can be based on a physical and actual object/environment or not; nevertheless, even if VR is based on a real object/environment, it is independent from that object/environment when it is formed. AR, on the other hand, is totally reliant on real-world objects and environments. AR allows us to digitally add something to a real-world environment; it is reality with something digitally overlaid on top of it (Eschena, H., et al., 2018).

VR and AR can be considered as a part of Digital Twin in more advance versions of Digital Twin. In some literatures, AR/VR technologies are mentioned as an important part of Digital Twin (Wang, K., et al., 2019).

2.2.4. Digitalization

Technology has an impact on people's lives in various ways. In the previous three centuries, the industrial revolution has had an impact on the environment and social traits. This revolution had a huge impact on economic systems (Jovanovic, et al., 2018).

Moving from one step to another in industrial revolution usually takes long time. It took, from first to second industrial revolution, something around 80 years. Industrial shift from step two to step three started to happen end of 19th century and ended early 20th century. In 1960s, third revolution began to happen with advent of computers and internet. This revolution is known as digital revolution or computer revolution (Schwab, 2017). In this revolution, that is not completed yet in 2020s, digital technologies play an underlying role. Technologies like: Big data, Internet of Things (IoT), Cloud Computing, Blockchain, Cyber-Physical Systems (CPS), and Artificial Intelligence (AI) (Kristoffersen, E., et al., 2020). Within this process there are three terminologies that need to be clarified: Digitization, Digitalization, and Digital Transformation. Figure 2-5 summaries these differences and in following subsections they are described briefly.

	DIGITIZATION	DIGITILIZATION	DIGITAL TRANSFORMATION
Focus	Data conversion	Information processing	Knowledge leveraging
Goal	Change analog to digital format	Automate existing business operations and processes	Change company's culture, the way it works and thinks
Activity	Convert paper documents, photos, microfilms, LPs, films, and VHS tapes to digital format	Creation of completely digital work processes	Creation of a new digital company or transformation to a digital one
Tools	Computers and conversion/encoding equipment	IT systems and computer applications	Matrix of new (currently disruptive) digital technologies
Challenge	Volume *Material*	Price *Financial*	Resistance to change *Human resource*
Example	Scanning paper-based registration forms	Completely electronic registration process	Everything electronic, from registration to content delivery

Figure 2-5: Differences between Digitization, Digitalization and Digital Transformation (Savic, D., 2019)

2.2.4.1. DIGITIZATION

"Digitalization" is the way of transforming analog data and information to a digital format. The digital data or information generated by digitization can be used in a variety of ways, in a variety of systems, and on a variety of materials (Brennen, J.S., and Kreiss, D., 2016).

2.2.4.2. DIGITALIZATION

Many individuals confuse the phrases "digitization" and "digitalization." "We refer to digitalization as the method in which various sectors of social life are reorganized around digital communication and media infrastructures," according to Brennen, J.S., and Kreiss, D., (2016, p1). "Digitalization is the use of digital technologies to modify a company model and generate new revenue and value producing opportunities," according to the Gartner Glossary. It's the transition from a paper based to a digital based industry."

2.2.4.3. Digital Transformation

Digital transformation is something more different from two prior terminologies and it is typically difficult for organizations to undertake as a specific project or process. With the support of digital technology, it is necessary to make strategic and high level changes in enterprises. Using digitalization in businesses, on the other hand, does not guarantee digital transformation. It necessitates organizational adjustments in areas such as culture, strategies, management, and operations, among others. Digitalization and new technology can help a company grow, but they can't change its core values (Savic, D., 2019).

2.2.4. Circular Economy (CE)

2.2.4.1. Definition of CE

The circular economy (CE) has been proposed as a viable alternative to the current linear economy of "take-make-dispose." "In the 2010s, the concept of CE arose as a way to contribute to long-term development" (Blomsma, F., et al., 2017). It has numerous objectives, including circular business models, sustainability, circular products and services, smart assets, and cross-sector supply chain collaboration. Finally, Kirchherr, J., et al. (2017) provided a thorough definition for CE, which can be found here: *"A CE describes an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, and recycling [...] materials in production/distribution and consumption processes, [...], with the aim of accomplishing sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations".*

CE purpose is to achieve sustainable development. A brief and general description of CE and its components are presented by Laskurain-Iturbe, et al. (2021), figure 2-6. They introduce five main elements of CE as five Rs: (1) Reduce Input Consumption, RIC, which includes material and energy consumption (2) Reuse, the purpose of this item is to extend the lifecycle of product (3) Recovery, this is somehow similar to previous item but may need some extra activities like remanufacturing and reconditioning (4) Recycling, extending the use of resources (5) Reduce Waste and Emission, RWE, this one is somehow the result of previous 4 elements, beside emission management strategies to reduce environmental effects. All these 5 Rs are highly related to each other and effect the main purpose of CE, that is shown in picture bellow, see figure 2-6.

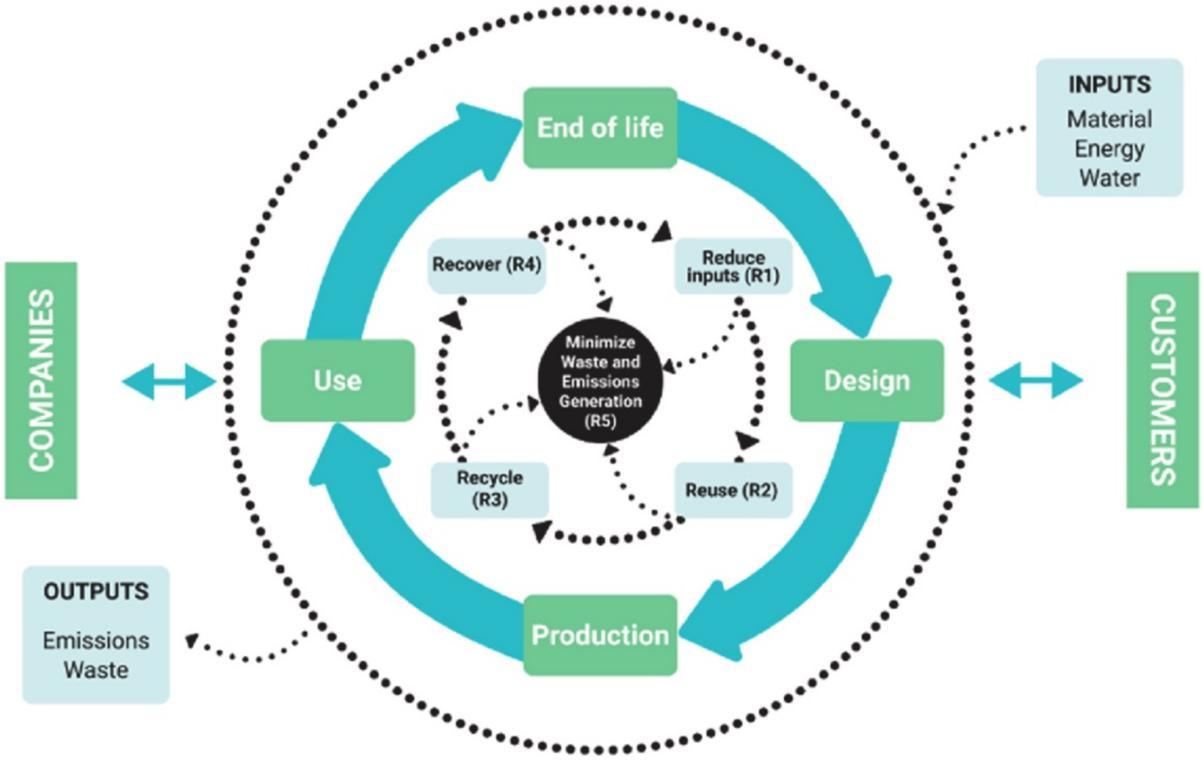


Figure 2-6: CE model (Laskurain-Iturbe et al., 2021)

2.2.4.2. CE Frameworks

CE is a high-level topic and bringing it down to satisfy small-business goals is problematic. The Circular Strategies Scanner, developed by Kristoffersen, E., (2021), is a CE framework that helps to break down this high-level concept. This structure is depicted in the figure 2-7 below. The first thing that stands out is that the entire structure is built around a large light green box labeled "energy," and a second box labeled "logistics." The relationship between distinct subsections can then be seen. Reimagine; rethink & configure; repair, minimize & avoid, recirculate components and goods, and recirculate materials are some of the subsections. These connections and priorities are best depicted in the diagram.

Circular strategies are divided in two groups: operational strategies and strategic applications. Reducing, restoring, and preventing effect in areas including sourcing, manufacturing, product usage, and logistics, as well as the recirculation of goods, components, and materials into new or existing use cycles, are all part of operational strategies. Rethinking and reconfiguring value-generating infrastructures, as well as creating the 'paradigm' for extreme decoupling, are strategic applications. To put it another way, the Scanner gives comprehensive support to industrial firms engaged in circular-oriented innovation (Kristoffersen, E., 2021).

Kristoffersen, E., (2021) creates The Smart CE Framework to integrate DTs and CE (see Figure 2-7). They demonstrate various levels of data transformation and data flow process levels employing digital technologies, and as a result, we gain resource optimization capabilities. The highest levels of optimization capability are "prescriptive" and "predictive," which can only be accomplished by data analysis wisdom.

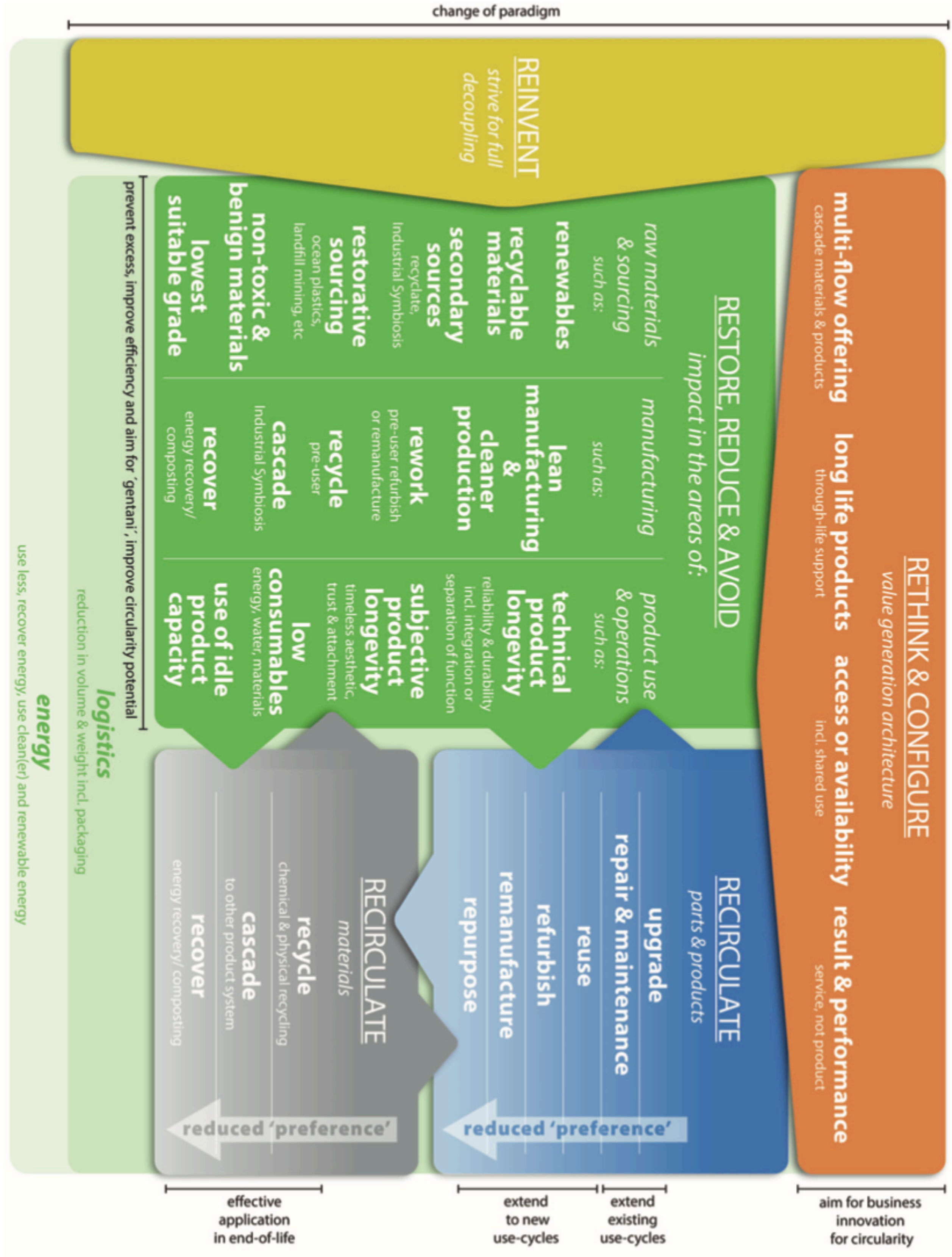


Figure 2-7: The Circular Strategies Scanner (Kristoffersen, E., 2021)

In their Smart CE Framework, Kristoffersen, E., et al. (2020) present an illustrated case of DT and human resource requirements. The third column is about "Data-Driven Maintenance," which aids in the goal of "Recirculate Parts and Products." To get to the smartest system, there are five levels of improvement:

1. At the descriptive level, DTs simply activate maintenance requirements in response to an alert of a sudden product failure. This capacity also extends to recognizing patterns in requirements.
2. The diagnostic level allows the system to identify operations that will extend the facility's life cycle. At this level, analysing usage behaviour is a human responsibility that necessitates the assistance of a knowledgeable individual.
3. At the discovery stage, investigate several methods for extending the life cycle. This level is classified as a condition management strategy. DTs and root cause analysis methods are utilized with operational data at this level. The maintenance standards for DTs are determined by human resources, who also carry out life cycle extension operations.
4. Predictive maintenance is the fourth level, where automating the planning life cycle is possible. The operational period is shortened, but the facility's life cycle is lengthened. Determining the maintenance guidelines for DTs is still a human resource duty at this level.
5. Prescriptive is the brightest stage in this system, where organizations acquire self-determination. With maintenance logs and failure data, deep learning techniques are applied. ML algorithms describe the maintenance roles of DTs at this level.

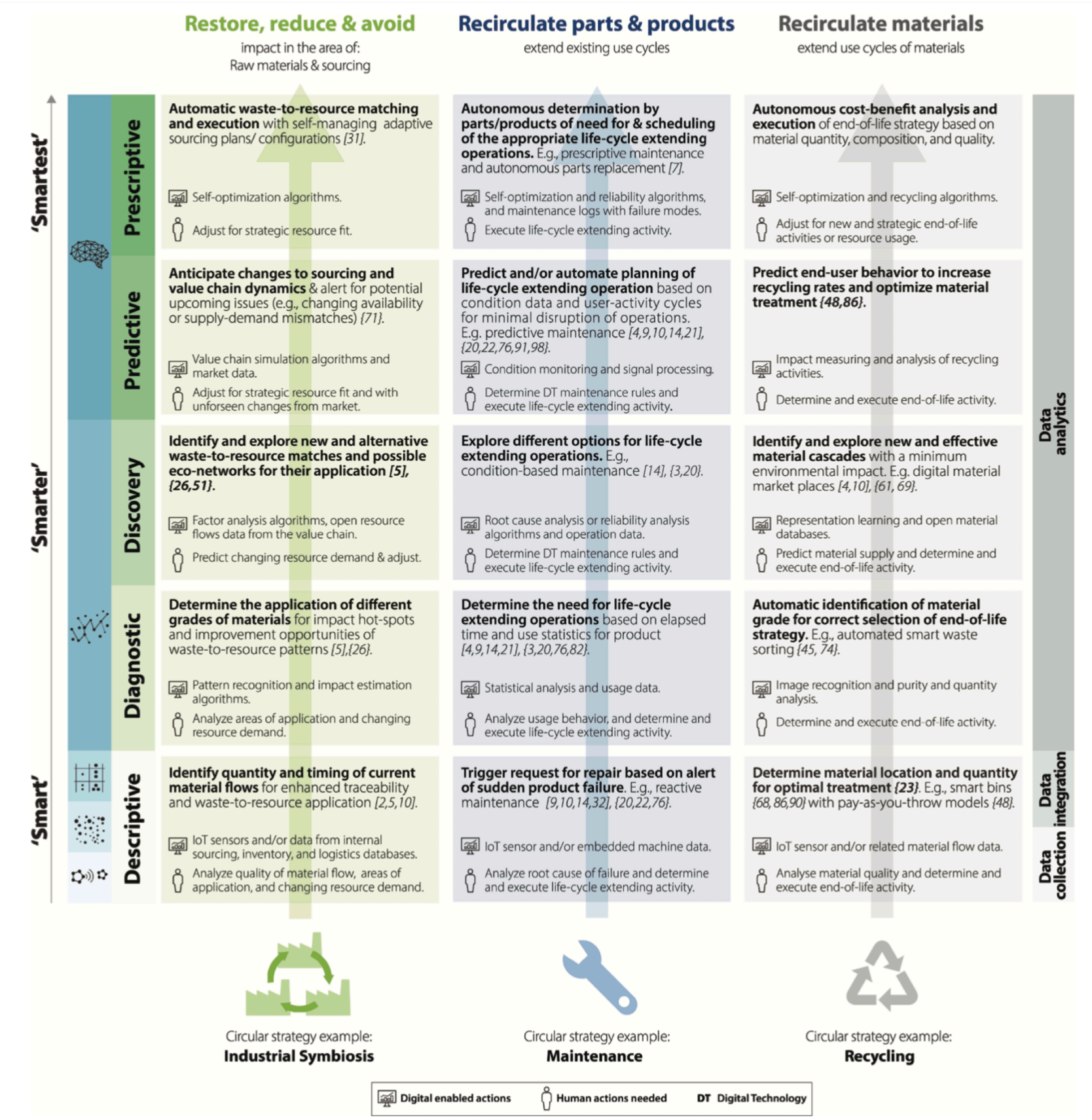


Figure 2-8: Practical examples based on Kristoffersen's CE Framework (Kristoffersen, E., et al., 2020)

2.3. Digital Twin

2.3.1. Digital Twin's definitions

"Digital Twins are Digital Replication of living as well as non-living organisms that enable data to be effortlessly exchanged between the physical and virtual worlds," according to one of the most general definitions of Digital Twins recently released by Scheper, T., (2021). So, Digital Twins are digital models developed to imitate a real-world object/environment, and they are fully reliant on reality, nothing more, nothing less, albeit they do avoid many unnecessary features in some literatures and practical scenarios. In the actual world, there is no limit to how many details may be examined, making the system computationally and graphically more complicated to analyze. Digital Twin has capacity to bring many factors to an integrated model (Lu, Q., et al, 2022).

Digital Twins are necessary to move AEC and FM into Industry 4.0, according to (Fjeld, 2020, p.13), because they offer capabilities like as simulation, decision assistance, automation, and integration. Meda, P., et al. (2021) present a novel style of managing construction in the AEC sector called Digital Twin Construction (DTC), which is based on Digital Twins. Digital Twins improve the efficiency and efficacy of 1) asset design and project planning, 2) execution, building, and integration, and 3) operation phase, which includes FM, by connecting physical assets and virtual twins in real time. Evans and colleagues (Evans, et al., 2019).

A historic growth of Digital Twin definition is found in literature review by Opoku, D.G.J., et al., 2021, where they presented 25 definitions of Digital Twin sorted based on year of publication. In following table, table 2-3, some of the main definitions are listed:

Table 2-3: Digital Twin Definitions, sorted by year (Opoku D.G.J., et al., 2021)

Reference	Year	Digital Twin definition	Application
Shafto M., et al.	2012	Digital Twin is an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin	NASA's integrated simulations
Lee J., et al.	2013	A digital twin represents a coupled model 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 and other available physical knowledge.	Predictive manufacturing
Canedo A.	2016	Digital Twin is a digital representation of a real-world object with focus on the object itself.	Industrial IoT lifecycle management
Brenner B. , Hummel V.,	2017	Digital copy of a real factory, machine, worker, etc., that is created and can be independently expanded, automatically updated together with being globally available in real-time.	Shopfloor management
Grieves M., Vickers J.,	2017	A set of virtual information constructs that fully describes a potential or actual physical manufacturing product from the micro atomic level to the macro geometric level.	Product lifecycle management
Bruynseels K., et al.	2018	Digital Twins represents a specific engineering paradigm, where individual physical artifacts are paired with digital model that dynamically reflects the status of those artifacts.	Health care management
Kaewunruen S., et al.	2019	Building information model (BIM) is a digital twin	Lifecycle management of railway turnout systems
Borth M., et al.	2019	Digital Twin is a connected and synchronised digital replica of physical assets which represent both the elements and the dynamics of how systems and devices operate within their environment and live throughout their lifecycle.	Architecture for cyber physical systems
Fotland G., et al.	2020	Digital Copy of a physical asset, collecting real-time data from the asset and deriving information not being measured directly in the hardware	Work environment safety
Liu M., et al.	2021	Digital entity that reflects physical entity's behaviour rule and keeps updating through the whole lifecycle.	-

2.3.2. Data Standards

BuildingSMART is a non-profit organization that establishes and maintains the most well-known BIM standards. Industrial Foundation Classes (IFC), which covers FM and BIM standards, is a previous and major standard they produced. The initial version of IFC was introduced in 1998, and the most recent version, IFC4.3.RC4, was released in July 2021. BuildingSMART is investigating in this open source data format and a bright future for that format is expected (Lu, Q., et al, 2022)

Model View Definition (MVD) is an IFC subset that contains schemas for exchanging data between applications. COBie, or Construction Operation Building Information Exchange, is a frequently used MVD that is related to FM. COBie documentation begins with the design phase, when architects add details about building components, and continues with revisions during the construction phase. COBie was officially adopted by the US National BIM Standard (NBIMS-US) in 2011, and British Standards (BS 1192-4:2014) followed suit in 2014.

COBie is a broad standard that may be utilized in a variety of settings and is simple enough to be used for spreadsheet interchange. It's a platform for sharing and exchanging structured data at any level, from the broadest and most general to the most specific. As a result, COBie allows businesses to store and transmit multi-layered spreadsheets of data. COBie spreadsheets can be exported and loaded into practically any well-known application.

COBie and IFC are well established in BIM applications. Patacasa, J., et al., (2021) created a framework based on COBie and IFC model to support FM in a real case study. Yu, G., et al (2021) extends COBie one step more in their framework to use Digital Twins with the purpose of O&M of tunnels. These standards are inseparable parts of FM frameworks. In most literature articles they are addressed directly and in some other studies they are indirectly mentioned.

There are several subcategories of mentioned standards in the market. CoClass[4], as an example, is one of the latest categorization systems for construction-related information. Swedish researchers developed and used this special customized version to support their needs. Another version is Uniclass-2015[5], that is used in UK construction sector. In Norway, another modified version of BIM standard is available as “NS 8360”[6] which is developed by “Standards Norway”.

In general, BIM is categorized as Computer-Aided Facility Management Systems (CAFM). Aside from COBie data import/export, a CAFM can have the following features: cost and financial controls, asset registration, asset monitoring, fault detection and reporting, operational plans, corrective maintenance plans, preventive and periodic maintenance plans, risk and hazard assessment, change management, work permits, identifying regulations, task order, task prioritization, task tracking, log of energy and material usage, resource analysis, planning an event, and task order, task prioritization, task tracking (Atkin, B., 2015, chapter 15). This is a thorough list of CAFM system features.

A comprehensive literature review about standards is done by Lu, Q., et al., (2022). They categorized standards in 3 categories. Standards related to (1) data exchange and

[4] https://byggtjanst.se/tjanster/coclass/
[5] https://www.thenbs.com/our-tools/uniclass-2015
[6] https://www.standard.no/en/sectors/bygg-anlegg-og-eiendom/digital-byggeprosess/ns-8360-bim-objekter/

interoperability, (2) asset management and (3) standards related to BIM. Figure 2-9 shows these standards. Asset lifecycle is also considered in this study within: (1) Design phase, (2) Construction phase, (3) O&M phase, and (4) Retrofitting / refurbishment phase.

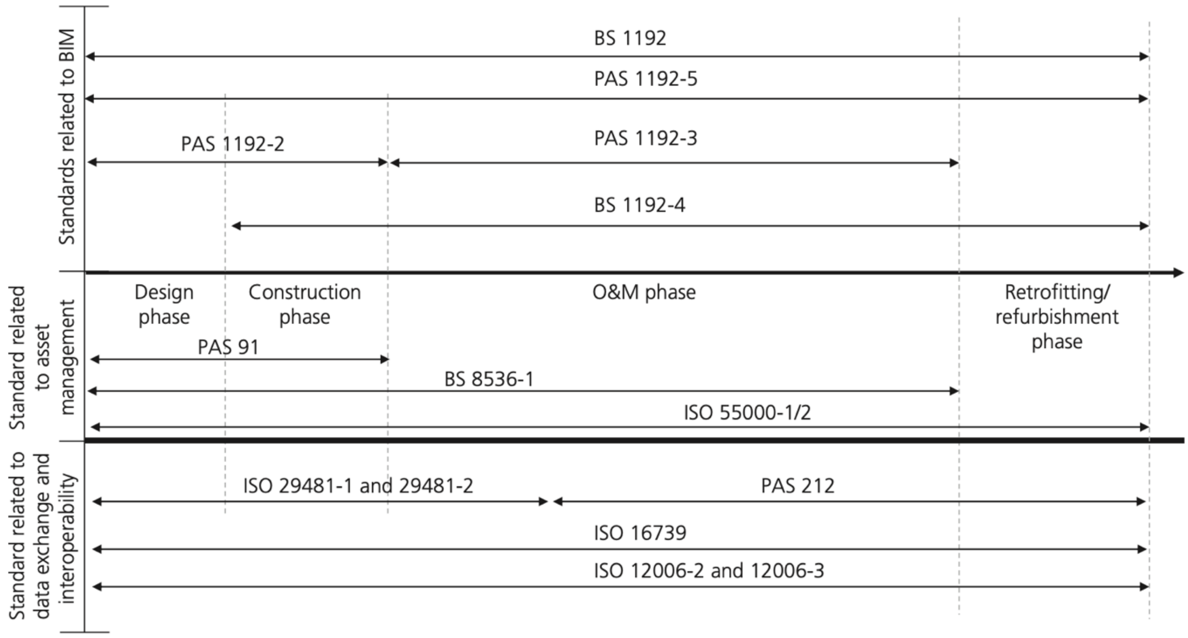


Figure 2-9: Summary of standards throughout an asset's whole life (Lu, Q., et al, 2022)

2.3.3. Classification of Digital Twins

In the literature, there are two main classifications for Digital Twins. The first is based on the exchange of data between a physical and a digital object. Tchana et al. addressed the idea of this classification, which was first offered by General Electric Digital Twins (2019). Different papers, such as Fjeld, 2020; Errandonea, I., et al., 2020; and Meda, P., et al., 2021; present this form of classification. Figure 2-10 shows the three types of digital models: digital model, digital shadow, and digital twin (Errandonea, I., et al., 2020 and Meda, P., et al., 2021).

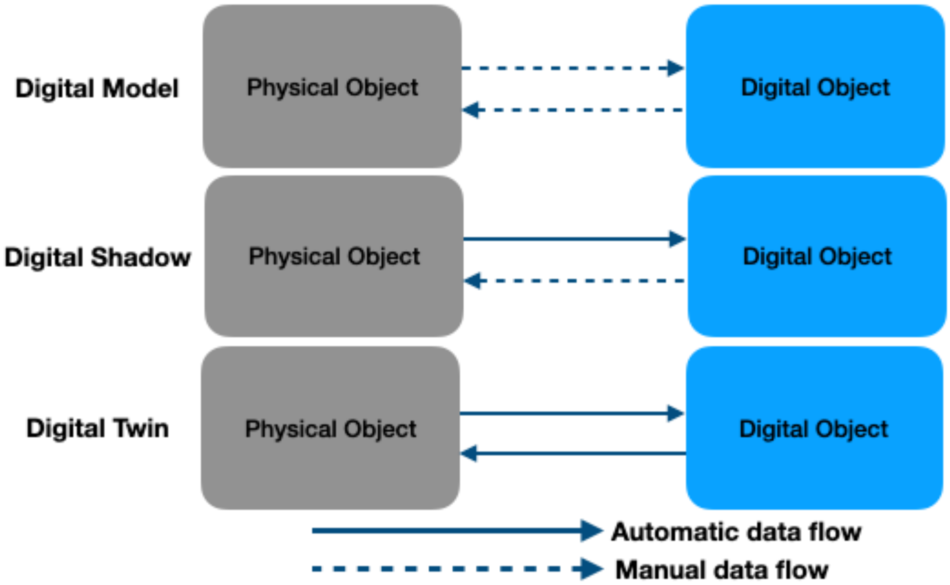


Figure 2-10: Digital Twin classification based on data flow
(Errandonea, I., et al., 2020; Mêda, et al., 2021)

Data flow from physical object to digital object and vice versa is manual in the first category, "Digital Model." Data transfer from physical item to digital object is automated in the second category, "Digital Shadow," but data flow from digital object to physical object is still manual. Finally, data frow in the "Digital Twin" category is automated in both directions.

Another category, "Digital Control," is defined by Fjeld (2020). Data flow is automated from a digital object to a physical object in this category, while data flow the opposite direction is still manual (see figure 2-11). This new category was not found to be relevant to FM difficulties and concerns, and a prior version of this classification with three categories was more often used in the literature, thus that version was employed in this research investigation.

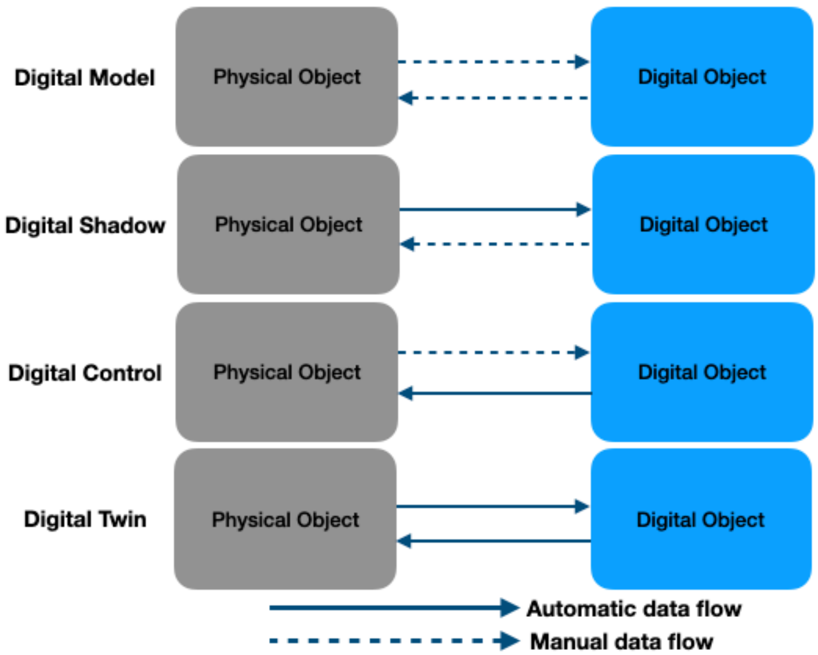


Figure 2-11: Digital Twin classification based on data flow (Fjeld, 2020)

The second categorization (Fjeld, 2020; Meda, P., et al., 2021) is based on the Digital Twin Maturity Index (DTMI), which is based on his research and interviews. Figure 2-12 depicts DTMI-based classification.

The concept of using a static BIM model to create an interactive and dynamic digital twin of our system is enhanced by Digital Twin. DTC is a customized form of Digital Twins that is equipped with IoT sensors and is a real-time model, according to Meda, P., et al. (2021). In general, it refers to Digital Twins with a level of equal to or greater than 300, as shown in Figure 2-12. As a result, a wide range of capabilities emerge:

- Real-time monitoring
- Greater health and safety achievement (safety can be improved by using image recognition)
- Better documentation and communication
- Predictive and scheduled maintenance
- Learn from data and identify patterns (and using AI/ML in the next step)
- enhance decision-making process (less uncertainty and risk)
- Improve equipment utilization (like daily activities and maintenance plan)
- Improve design in future projects

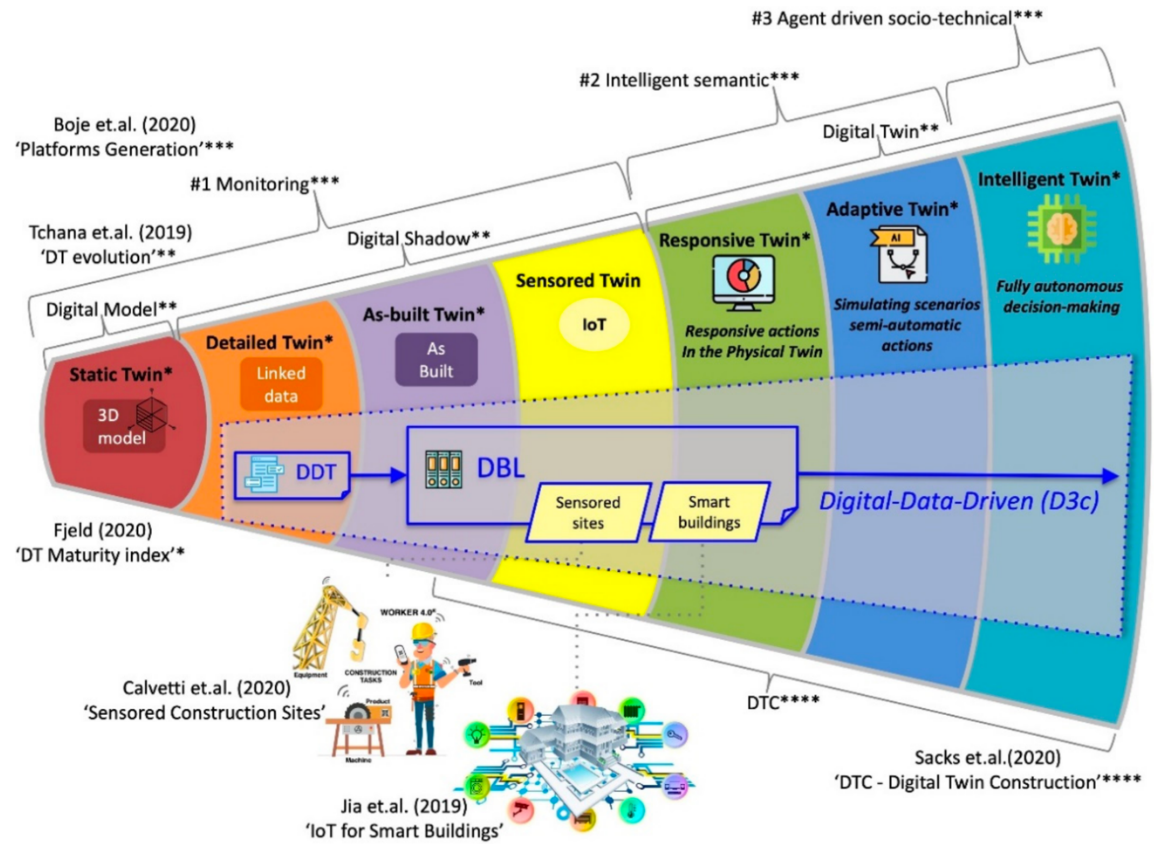


Figure 2-12: Digital Twins classification based on DTMI (Meda, P., et al., 2021)

In figure 2-12, Digital Twin is considered from 3 different perspectives. First perspective is: Monitoring, Intelligent semantic and Agent driven socio-technology. Another perspective is: Digital Model, Digital Shadow, and Digital Twin. Third perspective is seven levels that enhances from a 3D model to finally a fully autonomous decision-making model. In this incremental model, Digital Twin appears from level 5, where we achieve capability to make changes within physical model by the power of control on digital model. In conclusion, Digital Twin starts from the point that we create a two-way automated data flow in the system.

2.4. Digital Twin and FM

2.4.1. State of the art Digital Twins and FM

In different literature review articles raising adaptation of Digital Twin in AEC industry is mentioned (Errandonea, I., et al., 2020; and Zhao J., et al., 2022). 68 out of 197 literatures studied by Errandonea, I., et al. (2020) were dedicated to Digital Twins applications in Maintenance; the majority of these were related to asset prediction and preventive maintenance management. AR is used in some of these studies (Rabah et al., 2018; Sivalingam, K., et al., 2018) to predict future failures. Some achieve reductions in general maintenance activities by forecasting asset state and optimizing maintenance programs. Other applications indicated in Errandonea, I., et al. (2020) study include evaluated examples relating to maintenance process improvement, optimization of process methods, and cost estimations.

Lu, Q., et al, 2018, published an article with the title: “Activity theory-based analysis of BIM implementation in building O&M and first response”, where they investigate applications of BIM for FM. four years later, 2022, they published another article, Lu, Q., et al., 2022, with the title: “Moving from building information models to Digital Twins for operation and maintenance”. In this article they claim some limitations of BIM that supports moving to Digital Twin. Lu, Q., et al., (2022, *Smart Infrastructure and Construction*, Volume 174 Issue 2, page 53) “*Digital Twin is more suitable for complex and comprehensive data management considering the limitations of BIM listed earlier because Digital Twins are built on data and have the capacities of integrating various data resources.”*. BIM challenges (although they are still Digital Twins’ challenges too) are listed in table 2-4.

Table 2-4: BIM and Digital Twin challenges (Lu, Q., et al., 2022)

Main Challenges	Sub factors
Technology-related issues	Lacking a well-organised demonstrator and guideline for technology selection, design and integration
	Lacking integration of BIM with various CAFM systems
	Lacking integration of BIM with other systems – for example, locating and navigating in a complex BIM
	Lacking integration among various applied systems
	Lacking clear and logical plans for updating as-is BIM
Information-related issues	Lacking a predefined strategy of transforming different information – for example, natural languages, expert experience and digital dat
	Lacking a customised and extensible database for different types of information
	Information aspects in the CAFM systems not matching those in the BIM-authoring tools
	Lacking clear defined strategies for information saving, exchanging and sharing
	Lacking specifying LOD requirements for BIM in the O&M phase
	Lacking specific information requirements according to the organisational roles
	Lacking knowledge of specifying requirements of asset management early in the design phases
Organisation-related issues	Lacking understanding of learning processes for BIM in maintenance in the early building project stage
	Lacking an updated management mode (including people and facilities) for smart BIM-enabled asset management in the O&M phase
	Lacking updated working and services workflows for smart BIM-enabled asset management in the O&M phase
	Querying and updating routines are usually manual and time consuming
	BIM and systems are not fully integrated with the asset management workflow
Standard-related issues	Lacking a recognised standard/ specification determining the specific data requirements, BIM implementations, management processes and strategies
	Standards have often been developed for use within individual life-cycle stages and disciplines
	The developed standards are often generic in nature and fail to address the particular implementation challenges
	There is little to no alignment between the different standards, resulting in strategic documentation that does not align to process or technical requirements

S4AllCities, one of the most recent worldwide projects, brings together 27 universities and industrial companies from throughout Europe to create smart cities utilizing Digital Twins. This project began in September 2020 with three cities: Bilbao, Spain; Trikala, Greece; and Pilsen, Czech Republic. They use three separate Digital Twins for various reasons, with the ultimate goal of creating smart cities with a high level of safety and security. Using Machine Learning techniques, each of these Digital Twins is specialized on a unique problem. These are the three Digital Twins:

a) Distributed Edge Computing IoT Platform: DEC_IoT: This layer's IoT sensors and digital cameras monitor activities, and this Digital Twin is trained to process them.

b) Malicious Actions Information Detection System: MAIDS: This level specializes in distinguishing between typical and odd behaviour.

c) Augmented Context Management System: ACMS: They utilize Augmented Reality to detect potential dangers at this level.

Sabeur, Z., et al., (2021) concentrate on the Cyber Traffic Network and offer two modules for detecting cyber and physical anomalous behaviors in the context of the S4AllCities initiative.

Zhao, J., et al., (2022) developed a framework for Digital Twin to facilitate FM in AEC industry. Their research makes two contributions: (1) it gives an overview of DT applications for facility management during the O&M phase, as well as 4 case studies; and (2) it develops an evidence-based conceptual framework for FM. They claimed three main values that Digital Twin can bring to those cases are: (1) real-time data gathering and monitoring, (2) decision making, and (3) predictive maintenance. To facilitate implementation of Digital Twin in AEC industry and especially in O&M purpose, they presented a bottom-up framework, see figure 2-13.

There are not many practical applications of Digital Twin in the literature. One of the latest articles that implemented Digital Twin is done by Xie, X., et al. (2020), where they implemented their model in the West Cambridge site with more than 40,000 square-foot area. Their model facilitated asset anomaly detection in FM.

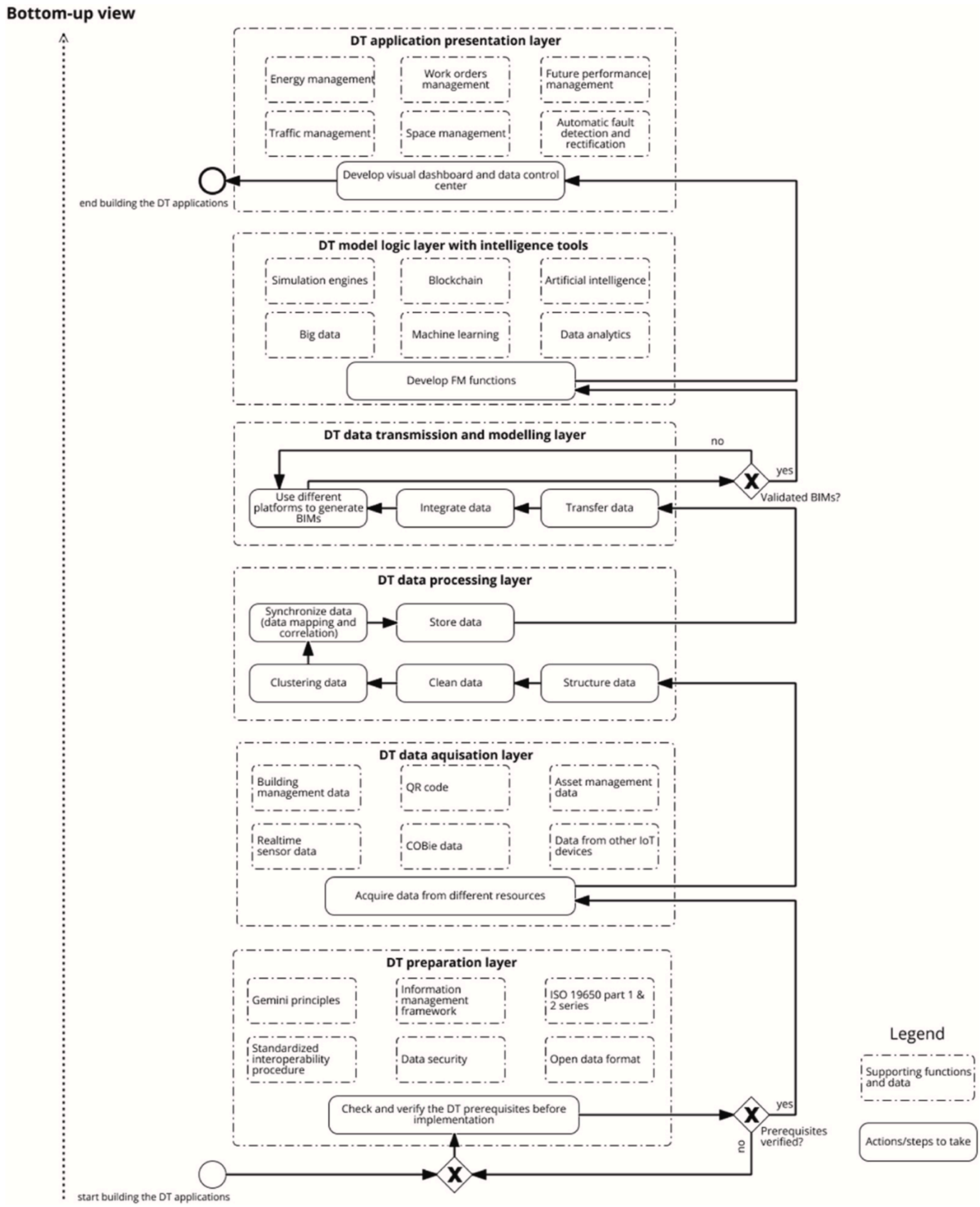


Figure 2-13: bottom-up framework for FM (Zhao J.., et al, 2022)

2.4.2. Digital Twin effects on CE

Digital technologies (DTs) are assisting industry in achieving higher levels of efficiency. More Efficient means reducing resource use while increasing system output, and continuing on this path to attain 100 percent recycling and zero emissions. This association between DTs and CE is investigated by Laskurain-Iturbe, et al., (2021). Figure 2-14 shows an example of one of their accomplishments.

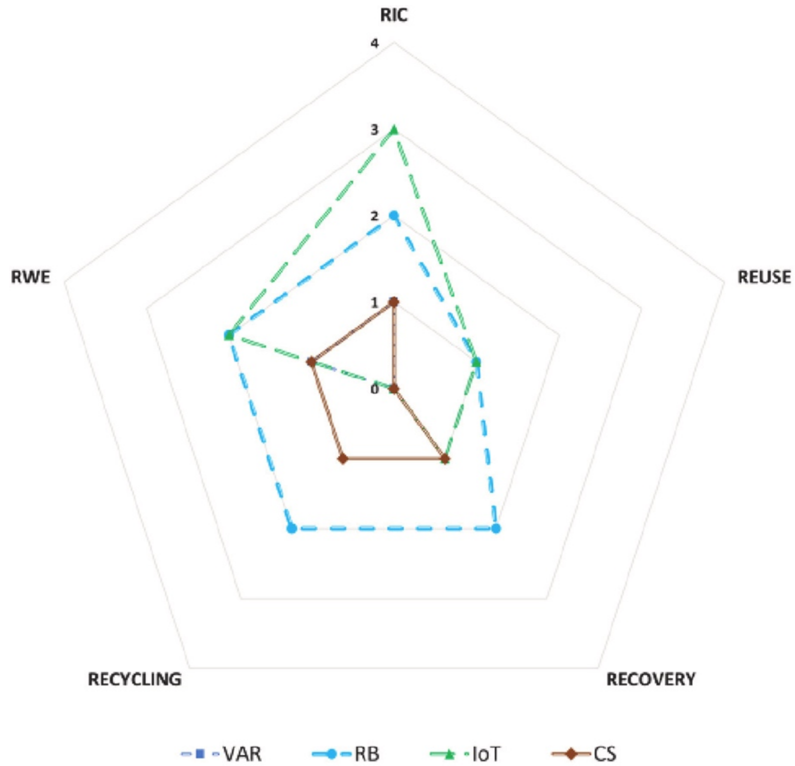


Figure 2-14: Relationship of DTs and CE parameters (Laskurain-Iturbe, et al., 2021)

On the one hand, Laskurain-Iturbe et al. (2021) define CE parameters as RIC (Reduce Input Consumption), RWE (Reuse, Recovery, and Recycling) (Reduce Waste and Emission). On the other hand, they examined four technologies: VAR (Virtual and Augmented Reality), RB (Robotics), IoT, and CS (based on 27 case study projects, 31 personal interviews with experts, and a literature analysis) (Cybersecurity). The impact of those technologies on CE characteristics can be seen in the diagram above.

3. Methodology and Research Approach

In this section, literature review, research design, and methodology of this study are presented. Finally, details about semi-structured interviews are presented. Ethical considerations for validity and reliability are important part of interview that are discussed in that subsection.

1.2. Literature Review

This research study is built based on first literature review, a mixed literature review, qualitative and quantitative review.

3.1.1. Different types of literature Review

Literature review is mostly defined as a systematic literature study that is divided into two main categories of qualitative and quantitative literature study. There is another subcategory, named narrative review, that many scholars mentioned that as a different and separate category (Bartunekl, 1993), but still some scholars put narrative review as a subcategory of qualitative review (Johnson, et al., 2017). Narrative literature review is conducted by prior experts in a field, those who done some studies in the same topic before and now are developing prior study (Green, et al., 2006).

3.1.1.1. Quantitative Review

Quantitative literature review is also addressed by some schoolars as Meta-analyses. This type of study collects a huge amount of data from literature study and makes analytical studies through that data. (Creswell, 2014)

3.1.1.2. Qualitative Review

Qualitative review, on the other hand, does not deal with a huge amount of data. It is not going to perform numerical studies. Qualitative review collects some limited literatures from different relevant topics to find a suitable answer for the research question. Case study is a very famous type of qualitative literature review. These types of studies investigate through some limited data, but so deep to find out their answer (Green et al., 2006; creswell, 2014)

3.1.1.3. Mixed Review

Another type of literature review is mixed research structure, that is presented by Johnson, et al. (2007). This type of literature review is using both above mentioned reviews and their strengthens. In this structure, some special and main references are selected and studied in deep, as well as searching through different sources to find out more holistic view on that topic. This research study can be classified under this category.

3.1.2. Research Design and Method

As mentioned by Tranfield, et al., 2013, using only high-quality articles does not lead to a good research study. Different publications including books, conferences, literature review articles are also needed to be used during research study. Thus, in this research study we are not limited to high quality articles only.

1.3. Data Collection

3.3.1. Literature Selection:

Different topics and concept around Digital Twin and Facility Management (FM) are found in literature review. There are not clear boundary between different concepts, and it is very difficult to mention one topic relevant and another topic irrelevant to Digital Twin and FM. Regarding this concern, VOSviewer software helped to get a clear picture of relevant topics. VOSviewer is a well-known software for analysing bibliographic data, data can be extracted from different databases like ScienceDirect, Scopus, Google Schola and NTNU Library (Oria). To get a better picture of articles around subject of this thesis, Digital Twin and FM, key words are searched in different databases and results are extracted and analysed in VOSviewer. The most relevant articles are found in the search key words “Digital Twin” and “Facility Management”. Figure 3-1 shows Digital Twin and FM results.

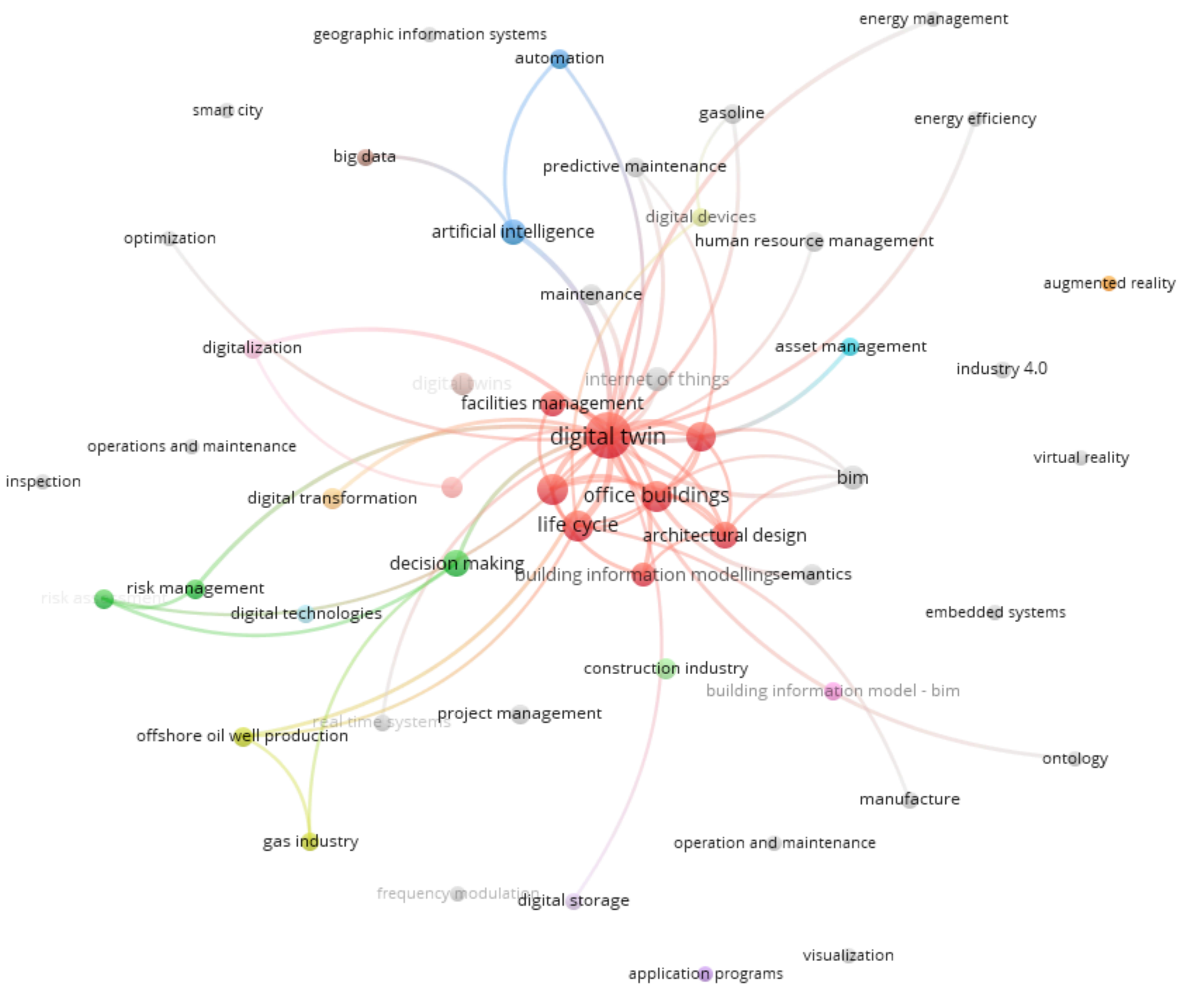


Figure 3-1: Digital Twin and Facility Management in VOSviewer

When minimum strength is increased to 2, weak links between keywords are gone and Figure 3-2 is the result. It is an interesting outcome that, Information Management, Office Building, Life cycle, BIM, IoT, Asset Management, Energy Management, Digitalization and Artificial Intelligence are the most relevant concepts.

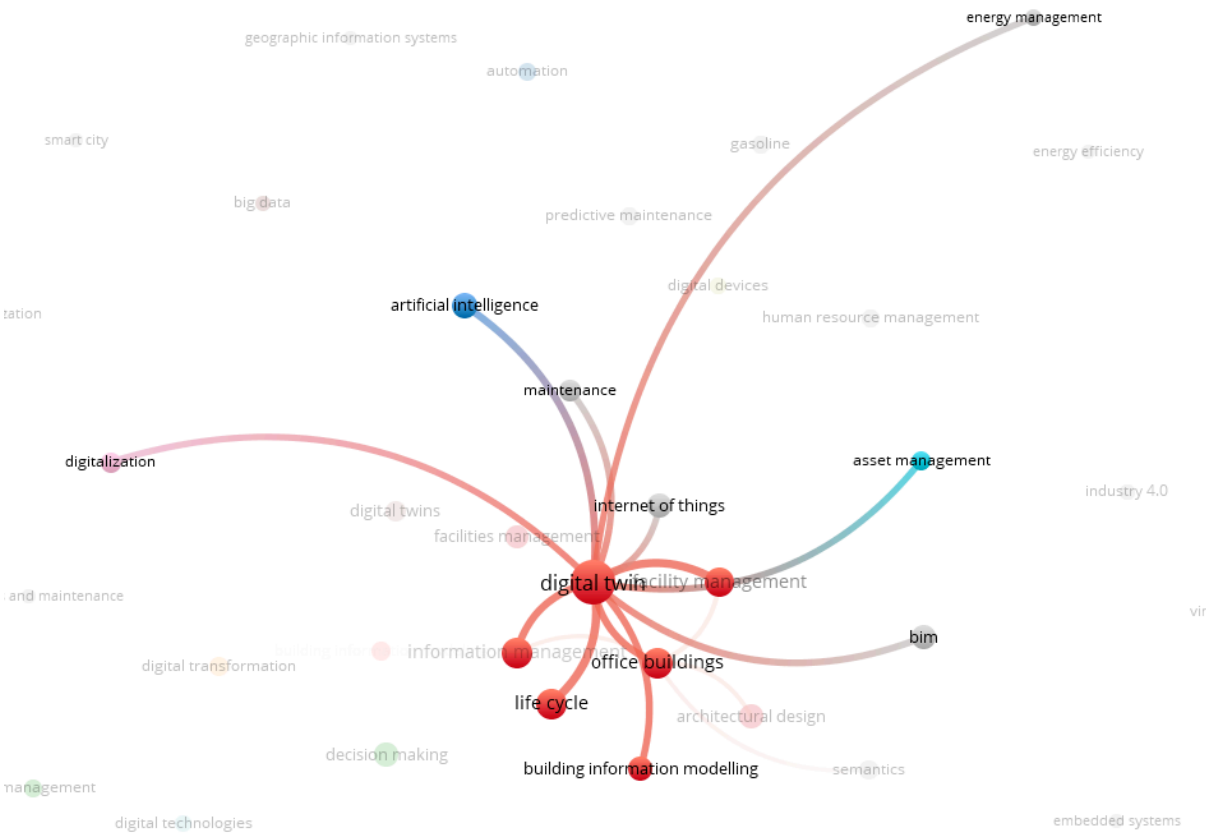


Figure 3-2: Digital Twin and Facility Management with min strength = 2 in VOSviewer

There are various types of customizations in the software's output. Different types of data with different measures are considered and three most relevant outputs are presented in figure 3-3. For each output different types of measures are applied, and results are analysed. These three pictures are chosen among more than 20 pictures. Combination of Digital Twin and Operation & Maintenance (O&M) are shown in top right corner, which shows all connections in keywords without any limitation (minimum strength is 1). Combination of Digital Twin and Facility Management (FM) is shown in top left, which limits connection between keywords to those with minimum strength equal 2. Combination on Digital Twin with Maintenance is depicted in downside of figure 3-3, which shows links with minimum 3 of strength. Here we realize maintenance is a more general word that can mislead the study. Although all three combinations that have been chosen are relevant and very helpful articles are found in all of these results.

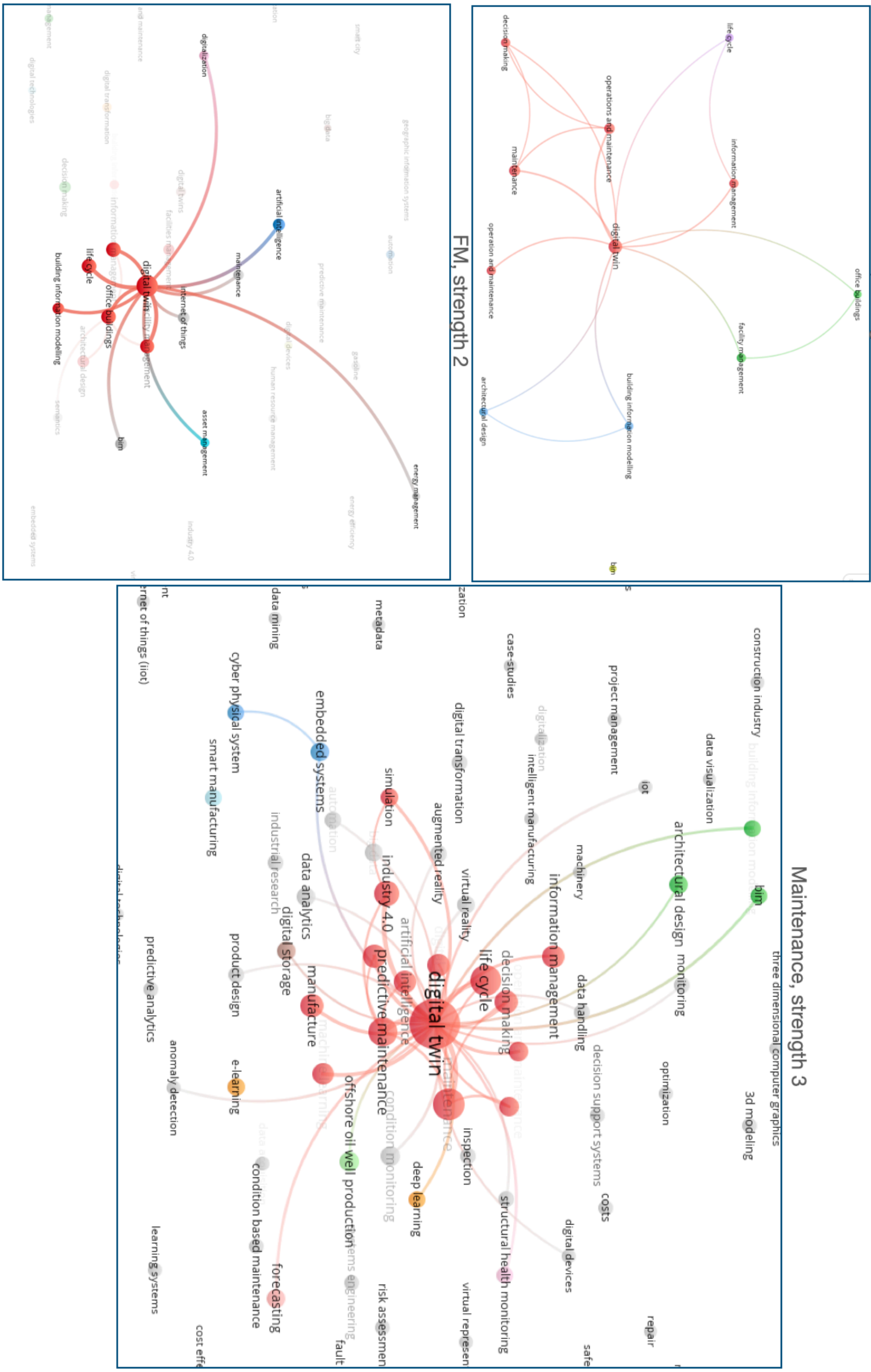


Figure 3-3: different keywords and limitation measures in VOSviewer

In order to conduct this research study, around 1000 materials are extracted from databases: Scopus, Oria, ScienceDirect and Google Scholar. Figure 3-4 shows exact numbers of search results, title review, abstract review and full read of articles. On the right column in figure 3-4 general number of three search categories are written. Generally, title of 215 of results are reviewed, abstract of 70 results are studied and finally 15 articles are selected and fully studied to be used in this thesis.

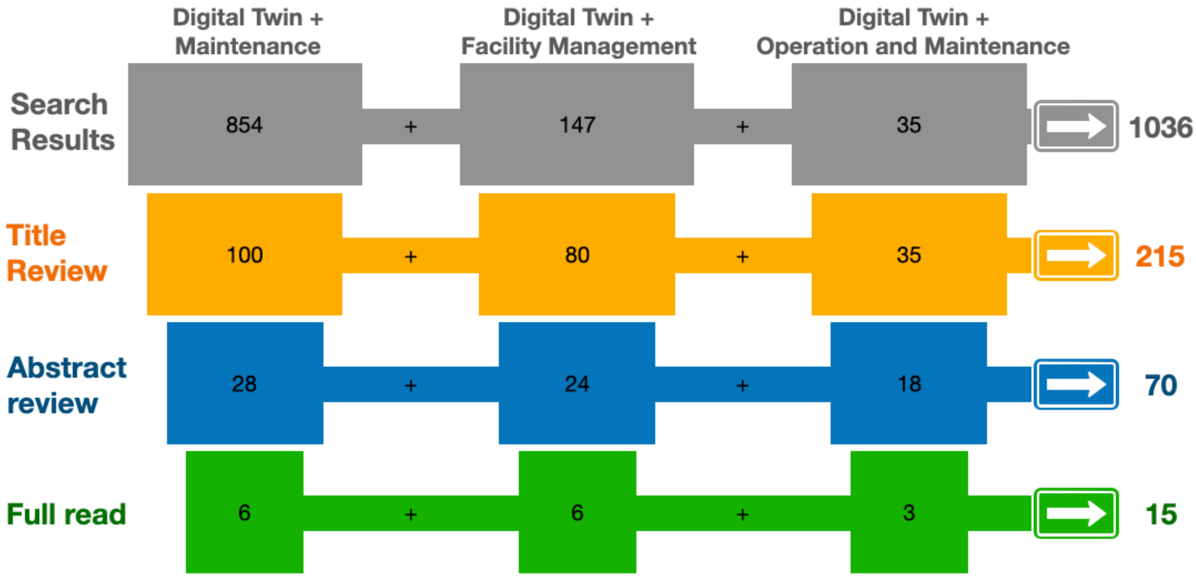


Figure 3-4: literature selection

Those 15 selected articles were totally relevant to this study. In table 3-1, total list of those 15 articles is written. Among those 15 articles, there were 2 literature reviews in this field, Digital Twin and FM that were great helps in this thesis (Errandonea, I., et al., 2020; Opoku, D.G.J., et al., 2021).

One special article by Lu, Q., et al. (2022), with very similar title also is one of the main selected literatures. The title of this article is: “Moving from building information models to digital twins for operation and maintenance”. This article is done by five PhD scholars from university of Cambridge.

Table 3-1: Selected articles

No.	Article	Year	Scope	Sector
1	Lu, Q., et al.	2022	Digital Twins and O&M	AEC/FM
2	Errandonea, I., et al.	2020	Digital Twin for Maintenance – Literature review	AEC/FM
3	Opoku, D.G.J., et al.	2021	Digital Twin for Construction – Literature review	AEC
4	Zhao, J., et al.	2022	Digital Twin and O&M	AEC/FM
5	Xie, X., et al.	2020	Digital Twin and FM	AEC/FM
6	Dzullkifli, N., et al.	2021	FM and Digital tools	AEC/FM
7	Fjeld, T. M. B.	2020	Digital Twins	AEC/FM
8	Parsanezhad, P.	2019	BIM and FM	AEC/FM
9	Patacas, J., et al.	2020	BIM and FM	AEC/FM
10	Ghorbani, Z., et al.	2022	Facility Management	AEC/FM
11	Yu, G., et al.	2021	Digital Twin for O&M of tunnel	AEC/FM
12	Meda, P., et al.	2021	Digital Twins and Construction	AEC
13	Broo D.G., et al.	2022	Digital Twins and Smart infrastructure	AEC
14	Shi, C., Wang, Y.	2022	Geological Data-Driven model	AEC
15	Rojek, I., et al.	2021	Digital Twins and Maintenance	Manufacturing

3.3.2. Interview Process

A series of in-depth interviews with various representatives and experts within the AEC industry were performed. The interviews were around 45 minutes in average, with the main theme being to explain and debate the concept of Digital Twin. Around 15 objects were contacted, but I was successful to arrange meeting with 10 of them. The interviewees were carefully chosen from private and public organizations or some of them as consultant. All interview objects had a significant interest in digital technologies and willing to help this thesis to facilitate using Digital Twin inside the industry. They're all known for their knowledge and talents, and they're all thought to have a strong profile in the AEC sector when it comes to research and development.

3.2.2.1. Overview of Interview Objects

In following table, table 3-2, background of interview objects and their fields of experience (some of them experienced all different phases of project) are presented. Firstly, about project phase, it is expected that one expert with more than 20 years of experience to have different phases of project in his profile as experience but based on the information we took and highlighted parts of interview, main project phases that expert focused were check marked in the following table. Secondly about category of each expert, the same as project phase, they were usually involved in different categories, but category that best match latest position of expert in his career, and especially main highlighted conversations during interview, is selected here.

Table 3-2: Interviewees and their background

		Project phase			Years of experience			
Obj.	**AEC**	**Design**	**Construction**	**O&M**	**5+**	**10+**	**20+**	**Category**
1	√	√		√	√	√		O&M
2	√		√	√	√	√	√	Design and Construction
3	√		√	√	√	√		Consultant
4	√		√	√	√	√	√	Consultant
5	√	√	√		√			Design and Construction
6	√			√	√			O&M
7	√		√	√	√	√	√	Consultant
8	√		√	√	√	√	√	O&M
9	√	√	√		√			Design and Construction
10	√		√	√	√	√	√	O&M

Figure 3-5 shows interview objects in 3 categories: Operation and Maintenance, Design and Construction, Consultant. All interview objects were experienced in AEC sector and most of them had different positions in their profile, but this categorization is done based on their last position and main highlighted points of their interview.

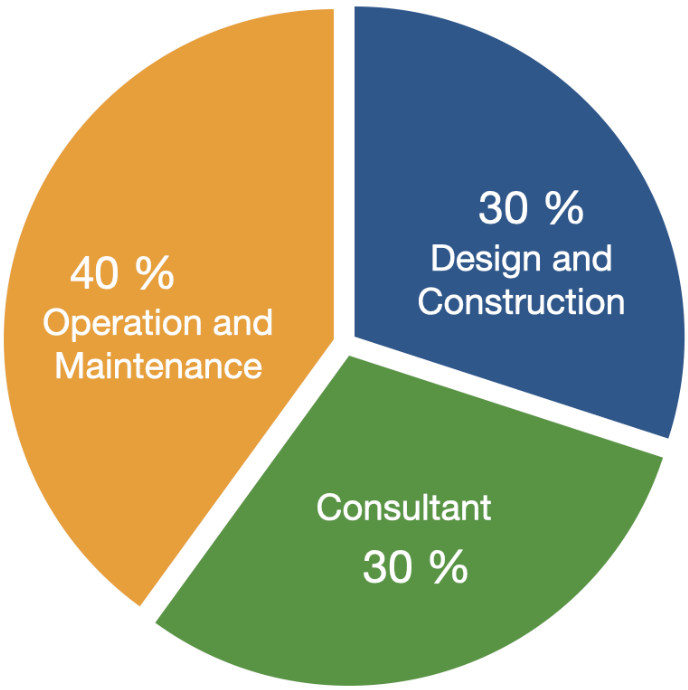


Figure 3-5: Categories of interview objects

3.2.2.2. PRIVACY AND ETHICAL CONSIDERATION

In the interview process, some protocols and practices need to be considered. Due to research rules and regulations in Norway, all researchers collecting personal data from interviewees must fill out a form in NSD (Norsk Senter for Forskningsdata). In order to contact interview objects and conduct interviews, this form is filled and NSD centre assessed information regarding this thesis and interview plan. Then, NSD gave us permission to perform interviews.

In the next step information about this study is sent to participants to become familiar with this research study. Also, their rights regarding NSD regulation and interview process are sent to them. Information letter including their rights and regulation are signed by both student and supervisor of this thesis. Interview objects who approved to participate in this study, had signed the letter and sent it back to student.

All personal data is saved on the NTNU infrastructure, such as OneDrive, SharePoint, and Microsoft Teams, for increased data protection and safety. The responses were used and analysed anonymously in this thesis. All recordings and personal data were deleted after the thesis is completed. All collected data from interview objects are presented in an anonymous way. their organizational position and relationships will not be noticeable.

3.2.2.3. VALIDITY

In a qualitative study, validity and credibility are essential, where in the words of Kumar, R., (2014, p.213), validity is "*the ability of an instrument to measure what it is designed to measure*". It is very improbable that all the researchers or participants to reach the same conclusion. Validating of qualitative research is even more difficult than validating quantitative research. However, there are various techniques that researchers can use to validate their study:

1- **Triangulation:** method of ensuring that the interview material is consistent by cross-referencing the interview data with information from additional sources like documents, observations, and even other interviews.

In this thesis, Triangulation is used multiple times between interview objects messages and literature articles as well as two literature reviews that have been found on this subject, Digital Twin for FM in AEC industry.

2- **Respondent Validation**: to check that the interviewer fully understands all the concepts and details offered by the interview objects, the transcription is sent back to the participants.

As interview objects were mostly experts in this topic, this method was not an option.

3- **Data Plausibility:** situation of interview objects in their field of experience and their knowledge. The high validity of the data is typically ensured by interviewing experts or individuals with extensive experience.

In this regard, we interviewed experienced people in the sector. 70% of interview objects had 10+ years of experience and 50% were 20+ years of experience.

4- **Looking for Themes in the Transcript:** this approach advises doing multiple interviews rather than relying on only one interview. So, researcher can use the data more confidently (Denscombe, M., 2014).

This is another technique utilized to ensure the quality of the data in this thesis was to search for themes in the transcript.

3.2.2.4. RELIABILITY

Reliability is ability of getting the same results under the same situations, if we repeat research multiple times (Kumar, R., 2014). Based on this definition, measuring reliability for this thesis is very difficult task, while it is almost impossible to repeat same situation with same people to do this study. Franklin, C., and Ballan, M., (2001) presented a method to increase reliability of qualitative data especially interview data collection. Their method is to examining responses of an interviewee using different forms of questions on same topic. So, to increase reliability in this thesis, while doing interview with experts, main questions were only 3 questions while interviews lasted around 45 minutes. During this time, we discussed same subject from different perspectives, and I tried to ask same question from different perspective.

1.4. Limitation

It was challenging to locate suitable interview objects with experience in Digital Twin, as well as with experience in Facility Management in AEC industry, since the number of organizations that were implementing Digital Twin was very small and since the focus of this thesis was more on practical perspective of Digital Twin, which is quite new topic in AEC industry.

The Covid-19 epidemic also made it difficult to conduct the interviews. Since many of the employees worked from home, network of people who were involved in the topic was limited. It was difficult to visit the companies and schedule an in-person appointment because many of the interview invitation emails went unanswered.

4. Empirical Results

In this section, findings from 10 interview objects are presented. Interview objects are experienced people from the Architectural Engineering and Construction (AEC) sector. Questions are formulated to find state of the art Digital Technologies and specifically Digital Twin usage in AEC sector.

As it has been found in literature review, Digital Twins gaining more attention of scholars in last years and it seems to be on a growing pace. But still, we can't find practical usage of Digital Twin in the sector.

Interviews had 3 main questions, (1) how sector defines Digital Twin, (2) What can Digital Twin bring to sector, and the most importantly (3) what are the challenges for bringing Digital Twin in the real project? For all mentioned questions there were some follow up questions (including information from literature review) to enable interview objects to reflect of findings in literature and add more information.

1.5. Digital Twin Definition

Most of interview objects were experienced people who working with Digital Twin in AEC sector. A brief and the clear definition of Digital Twin was: "a dynamic Digital representative of a physical object". The focus on "dynamic" or "living" representative were something bold in their answer. Interview object 1 mentioned that Digital Twin is not only a BIM, but it should also have real time data from IoT sensors that integrated with BIM model. S/He referred to STATSBYGG[7] which is "*Correct and updated representative of the building*". Big companies like Microsoft and MATLAB are working on developing their own Digital Twin platform. MATLAB also created an eBook for Digital Twin[8]. Also, interview object 8 referenced his/her definition to Digital Twin Consortium[9] that developed a very good definition of Digital Twin one year ago.

Interview object 3 mentioned Digital Twin is not mature enough and a solution is to define different types of Digital Twin. For example, in AEC industry and with the purpose of construction we should represent Digital Twin Construction (DTC). DTC is presented by Sacks, R. et al (2020). Meda, P., et al (2021) presents a DTC incremental maturity levels diagnosis framework to streamline Digital Transformation.

Digital Twin's role in representing information in a very human readable way. That is one main part of experts' mindset about Digital Twin. So, this aspect would help FM to a great extent, as mentioned by Ghorbani, Z., et al. (2022) finding required information for FM tasks has a great influence on FM work order efficiency. Regarding this value of Digital Twin to FM, more is discussed in next section, 4.2. Values.

[7] The Norwegian Directorate of Public Construction and Property is a Norwegian government agency that manages central parts of the real estate portfolio of the Government of Norway.
https://www.statsbygg.no/about-statsbygg
[8] https://explore.mathworks.com/digital-twins-for-predictive-maintenance
[9] https://www.linkedin.com/company/digital-twin-consortium/

Another takeaway of their definition was missing FM capabilities of Digital Twin. Digital Twin alone (based on definition) is not FM tool. Although all of interview objects pointed at positive influence of Digital Twin on FM, it is not mentioned as a part of Digital Twin definition. Among all interview object, interview object 2 had unique idea. S/He mentioned O&M and specially FM, compared to construction, doesn't cost much in the sector. The main cost is in the construction phase, and we should use Digital Twin with purpose of redesign (for renovation projects) as well as construction phase of projects. Also, interview object 6 and 7 answered they haven't seen such system and they suggested to have one FM tool connected to Digital Twin. For sure, this connection would be a two-way connection, on the one hand FM tool helps to have better visualized version of our system, also on the other hand, a better visualization helps FM system to operate more efficient.

Table 4-1: Definition of Digital Twin

Object	Source	Definition of Digital Twin
1	Direct quotation	*"Correct and updated and complete digital representation of a building. It is not just a BIM; we need to use IoT sensors and integrate its data with BIM."*
2	Paraphrased message	S/He mentioned that there is no clear and precise definition of digital twin.
3	Paraphrased message	No specific definition, because of "*low maturity*", we should have different types of Digital Twin, for example in AEC sector and for construction purposes we should use DTC (Digital Twin Construction). S/He refer to Meda P. et al (2021)
4	Paraphrased message	Something that we have digital technology connected to a 3D model, not specifically using IoT sensors. Digital Twin can be seen as a hub, that enables system to link different software and sensors together.
5	Direct quotation	*"In our contracts, sometimes Digital Twin is mentioned but there is no real definition anywhere."*
6	Direct quotation	*"An accurate 3D model that present current situation of building."*
7	Paraphrased message	Digital representative of an object. Something not limited to one specific subject like energy or FM or …. Something with a holistic view that has continues change. It must live. If it is a static snapshot, it's not a Digital Twin.
8	Paraphrased message	Digital Twin is a result. Where you put thing together. Digital Twin should include geometry data on a 3D model as well as a database of different data.
9	Paraphrased message	S/He didn't mention anything clear bout Digital Twin, s/he mentioned they work with BIM and enterprise BIM
10	Paraphrased message	The Digital Twin's definition depends on the project's phase. You can call it the place to put all the documentations together.

In table 4-1, abstract idea of all interview objects is presented. It was very difficult to standardize all messages because all messages were from different perspective. In second column, "Source" is mentioned. Some definitions are "direct quotation" of interview object, and some of them are "paraphrased message" of interviewee.

1.6. Digital Twin Values:

Values that mentioned by different interview objects are presented in table 4-2. Again, second column in this table, source, mentions if the message is direct quote of interviewee or paraphrased message. Those are abstracts ideas and some of them need more explanation that are mentioned in following paragraphs.

Table 4-2: Values of Digital Twin

Value	Sub factors	Source
Information	Better access to information for end user	1, 6
	Better understanding of situation and process	4, 10
	Better professional collaboration	4, 6
	Internal and external collaboration	4, 10
Organizational Structure	Digital Transformation	3, 10
	Bring many factors together to get better picture of system	7
	Decision making	7
Others	Connecting to many external applications (like: Circular Economy and GIS)	7
	Safety and security process	4
	Green sustainable buildings	4

The most common idea about values that Digital Twin can bring to practice was related to data and information. This value can lead to better collaboration, internally and externally as well as better decision support (objects 4, 6 and 10). Actually, a better information can lead to many indirect benefits. Beside work order efficiency that mentioned prior, better training and more qualified meetings between decision makers are indirect benefits of Digital Twin.

Second common answer to this question was merging different factors to have more realistic view. Interview object 7, explained this value using a vivid example of temperature. Temperature is not the only parameter that leads to end user's feeling in the building. Humidity and number of people in the building are other parameters that effect end user's feeling in the building. Temperature could be fine but high humidity and crowded building can make people feel hot in the building. So, Digital Twin can help to bring all parameters together in a unified platform to take a clearer picture of what is happening in the physical object.

Interview object 4 mentioned another specific value that Digital Twin can bring to system, health, safety, and security. They integrated alarm system and sensors with Digital Twin in a real project in 2014. In the case of fire, for example, that enables system to detect danger area, and growing direction of fire. That makes safer and better evacuation of people as well as extinguishing fire more efficient. Interview object 4 also mentioned he has another experience using Digital Twin in a project with the purpose of green sustainable building.

1.7. Challenges

Interview objects were experts in this area and when they were talking about challenges, they introduce solutions as well. In literature review capabilities and values of Digital Twin are evaluated to a great extent, so the main reason of this research study to find challenges and challenges of having Digital Twin in the real world.

Following table, table 4-3, shows abstract challenges that are mentioned by interview objects. Two main categories, education and standardization are separated with different sub factors. This table is to summarize the output of interviews, but for better understanding each challenge and sub factor are described from every interviewee's perspective.

Table 4-3: Challenges of Digital Twin

Challenges	Sub factors	Source
a. Education	a. Change management	1, 9
	b. It is too complicated for the sector; we need to educate technicians	3, 7
	c. Introduction of Digital Twin to Project owners	4
	d. IFC format is vague and needs more clarification and education	6
b. Standardization	a. Different information sources	5, 8
	b. Maintaining Digital Twin is a challenge (no procedure)	6
	c. IFC format is one-way editable	6
c. Others	a. Projects are not ready to go for it in O&M phase, construction phase is the focus of sector	2

Interview objects 1 mentioned one common challenge is how to implement Digital Twin with regards to different characteristics of organizations and businesses. S/He also added, aspiration, (understanding, vision, or objective) of company is very important too. Company should be eager to implement Digital Twin. This leads to next challenge, based on interview with object 1, which is change management. Culture of using Digital Twin should be developed within the company. Even creating the best Digital Twin is useless and ineffective if the users don't use that, and it's not going to be a successful implementation. Interview object 1 denoted the importance of considering People, process, and technology all together.

Interview object 3 also mentioned the first step is to increase understanding and social awareness of Digital Twin. Otherwise, you go into technology silence. Interview object 4 also mentioned there are no special challenges for Digital Twin, and we just need to introduce it to the sector and project owners. Interview object 3 also mentioned we need to start simple. Complicated Digital Twin could be a huge burden on sector. In each project, they need to denote the least amount of data to start with. The main idea should be to start simple with some data input, then start analysing it and making progress. Based on whole interview with object 3, this road map leads organization to some positive points. First, they learn Digital Twin and how to use it. Second, they understand its positive impact on the system. And finally, they move forward toward Digital Transformation.

Interview objects 5 and 8 mentioned that building Digital Twin needs a lot of information from different vendors, different sources. Interview object 8 also pointed that we have different measurement units in different countries, and this is an important challenge that can be solved by standardization. S/He mentioned in ISO, in technical committee 59, Subcommittee 13, which is the subcommittee that runs BIM, they are trying to create a working Group number 9 that is specially for Digital Twin.

Interview object 6 also pointed at almost same challenges, which mentioned by objects 5 and 8, with different perspective. Object 6 mentioned it is not challenging to build Digital Twin, main challenge is to maintain it and keeping Digital Twin up to dated. There are many parties affecting Digital Twin, so it is difficult to maintain this model. Interview object 6 also mentioned having fewer operation staff that are comfortable with digital tools makes this process more challenging.

Interview objects 6 and 10 denoted they have problem using IFC format as well. Object 6 mentioned it is a one-way editable format. That's one reason for his idea about maintaining Digital Twin being challenging. Object 10 stated IFC format is a very ambiguous format. There is no one common way to use this format. It can be interpreted one model different in another project.

Before moving forward to next challenges, it should be mentioned, object 10 was very positive about standardization. He mentioned IFC format is getting better and better because STATSBYGG in SIMBA project tries to facilitate it. Also, he mentioned Norwegian Standards (NS), that is based on ISO standards and EU standards, are well established in Norway. STATSBYGG is on its way to describe this in a very good and solid manner and recently they lunched SIMBA 2.1[10] (April 2022).

Interview object 7 stated education and awareness of Digital Twin is the biggest challenge. He mentioned Digital Twin is invisibly tied to social Digital Transformation. He said we don't know how to leverage Digital Twin. He mentioned AEC sector is very busy sector with low margin. That makes Research and Development (R&D) to happen slowly in this sector. The idea of education and Digital Transformation is formed in this research study after this interview. This is something mentioned also by object 9. He denoted this sector is very busy and quite conservative, it's not very much innovation.

[10] https://www.statsbygg.no/nyheter/statsbyggs-bim-krav-i-ny-drakt

4.4. Results of interviews

Each interview object was an expert with different mindset and each one had a specific message that helped me writing this thesis. In following table 4-4, that specific message from each interview object is presented. Some of these messages are also pointed at previous sections, values, and challenges. But these messages were worthy to be emphasised again.

Table 4-4: Main messages of interview objects

Object	Main message
1	"*Information is like bloodline for Digital Twin (not too much, not too little). Too much information leads to blood pressure and too little information kills the body."*
2	*"Big money is in construction, Digital Twin can help in construction more than O&M. Specifically for renovation of buildings"*
3	*"Digitalization is combination of technology, people, and process. All this is about communication. One thing about communication is that you learn from it. So, I do think we should see this more as emergent living system."*
4	*"You can see Digital Twin as a HUB to get access to much more capabilities, for example VDCnordic (Virtual Design and Construction)"*
5	*"After 6 years they (customer) come back to architect who designed a building and ask him to update the design."*
6	*"Main value of Digital Twin: better communication and better handling of documentation"*
7	- *"Digital Twin is not isolated viewpoint, it's not only, for example energy or FM. For each of them separately you can do optimization. But when you start working with multiple factors that have interconnectivity and potential influence. So, Digital Twin is not a HUB, it is a result."* - *"Digital Representative is not perfect, it is not never perfect, there is always a margin of error. We should decide where do we need to stop."*
8	- *"Microoft AZUR is working on Digital Twin, and this would be the future of Digital Twin."* - *"And please involve software companies in your research, they need to change the market"*
9	*"people are the biggest problem"*
10	- *"Digital Twin's definition depends on the phase of project. Definition during construction is different from O&M phase."* - *"Handover and transition between these two are not well defined."*

5. Discussion

The aim of this study was to find out situation of Digital Twin in practice of Facility Management (FM) in Architectural Engineering and Construction (AEC) industry. On this regard answering three questions were formulated:

RQ1: How to Facilitate Facility Management using Digital Twin?

RQ2: What are the benefits of using Digital Twin for FM?

RQ3: What are the challenges of Digital Twin in the sector?

Answering first question requires to have answers of second and third questions. When we know benefits and challenges of Digital Twin, then we can try to answer question of "How". In order to answer these questions literature review have been done as well as 10 interviews with experts in this subject. In this chapter findings in both literature reviews and interviews are discussed. In section 5.1. concept of Digital Twin is discussed based on both viewpoints of literatures and experts. Section 5.1. is an important requirement for answering RQ2 in section 5.2 as well as answering RQ3 in section 5.3. Then, answering RQ1 is entwined with RQ3 answer; that is discussed in section 5.3 as well.

5.1. Concept of Digital Twin

In literature review, several articles are found with purpose of connecting Digital Twin to FM, and Operation and Maintenance (O&M). Almost in all Digital Twin frameworks found in literature (Lu, Q., et al., 2022; Meda, P., et al., 2021; Zhao, J., et al., 2022; Xie, X., et al., 2020) Digital Twin integrates Machine Learning and AI to facilitate asset management. To evaluate this concept of Digital Twin and compare with empirical results, I refer to Digital Twin maturity level presented by Meda, P., et al. (2021).

<table>
<tr><td rowspan="4">Digital Twin
Incremental maturity levels by Meda P., et al., 2021</td><td colspan="4">Monitoring</td><td colspan="2">Inteligent Semantic</td><td>Agent Driven Socio-Technology</td></tr>
<tr><td>Digital Model</td><td colspan="3">Digital Shadow</td><td colspan="3">Digital Twin</td></tr>
<tr><td>Level 1 Static Twin</td><td>Level 2 Detailed Twin</td><td>Level 3 As-Built Twin</td><td>Level 4 Sensored Twin</td><td>Level 5 Responsive Twin</td><td>Level 6 Adaptive Twin</td><td>Level 7 Inteligent Twin</td></tr>
<tr><td>A geometric 3D representative of physical object</td><td>+ information to have more detailed object</td><td>+ all historic information about components</td><td>+ sensors to have real-time model</td><td>+ capability of control physical model and alter components, using digital model</td><td>+ fully automated data flow between physical and digital objects</td><td>+ self learning and self regulating model</td></tr>
<tr><td>Digital Twin defined by Interview Objects</td><td colspan="2">Required for Digital Twin</td><td colspan="2">Digital Twin</td><td colspan="3">More than Digital Twin</td></tr>
</table>

Figure 5-5-1: Digital Twin Concept by literature (reference to Meda, P., et al., 2021) compared to Empirical Results

In figure 5-1, Digital Twin presented by practitioners is limited to level 3 and 4 of what presented in literature. It doesn't mean Digital Twin can't reach level 7, but reaching level 7, Intelligent Twin is something far beyond FM in AEC industry. It means Digital Twin needs integration with some other tools or systems to reach that level. From another point of view making level 7, Intelligent Twin, just in the purpose of FM in AEC industry may not be compiling enough for the sector. This paragraph was more general comparison, but there are still some details to be considered.

On the one hand, when talking about "Sensored Twin", it is not a zero/one situation. For example, if we have 80% of components within system equipped with sensors, then, do we have "Sensored Twin"? Or we should get 100% done?

On the other hand, for each component, there is unlimited details that we can collect and bring to Digital Model. For example, if we consider a room, as a component of system, and we install temperature, humidity, noise, and light sensors inside that room, is it enough?

To conclude, there is no clear boundary between dynamic and static model. Big difference has been found between **construction viewpoint** and **O&M viewpoint**. Constriction phase takes probably 6 month or one year, but when talking about O&M phase it could be several decades of operation. Thus, Digital Twin with construction purposes and Digital Twin for O&M purposes should be separated. To enable dynamic data flow between physical and digital object, using IoT sensors is not the only solution for all cases, some other alternatives may can help. In construction phase, using drones or even 2D pictures could be solution (using technologies like Shi, C., et al., 2022).

5.2. Benefits of Digital Twin

Benefits and challenges of Digital Twin are not well investigated in the literature. Focus of found literatures is about defining Digital Twin and presenting a conceptual framework for that. So, to discuss about benefits of Digital Twin we consider outcome of limited number of literatures that have been found. Firstly, Preventive Maintenance can be noticed to be mentioned as one main benefit of having Digital Twin (Xie, X., et al., 2020; Zhao, J., et al., 2022; Lu, Q., et al., 2022). But this value didn't noticed as a direct outcome of building Digital Twin. To conclude what we got as Digital Twin values and what we found in literature, table, and table 4-2 values from empirical results, we came up with following figure, figure 5-2, that shows potential values of building Digital Twin in the system.

But, to directly achieve FM-benefits, like Preventive Maintenance, Digital Twin should be integrated with a FM-tool, CAFM. In this regard, more presented in section 6, conclusions.

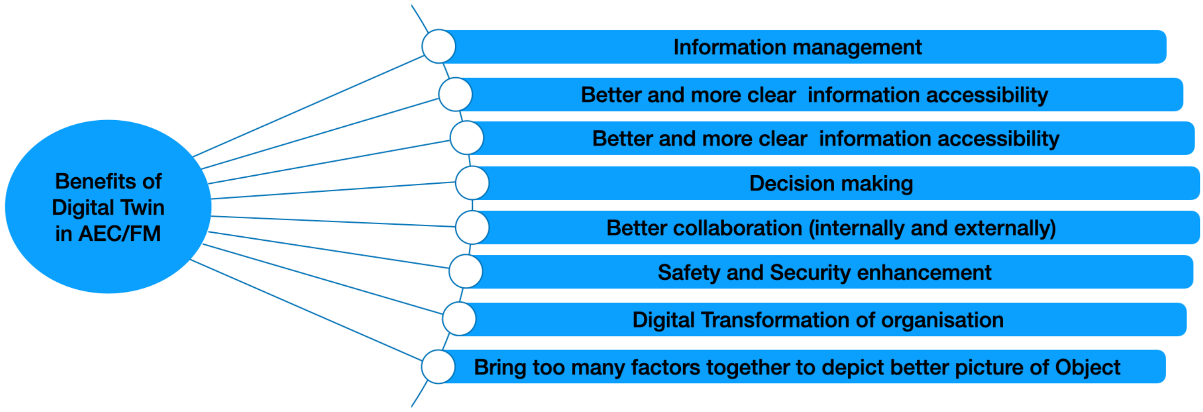


Figure 5-5-2: Benefits of Digital Twin for AEC/FM (Own Creation)

5.3. Challenges for bring Digital Twin to practice

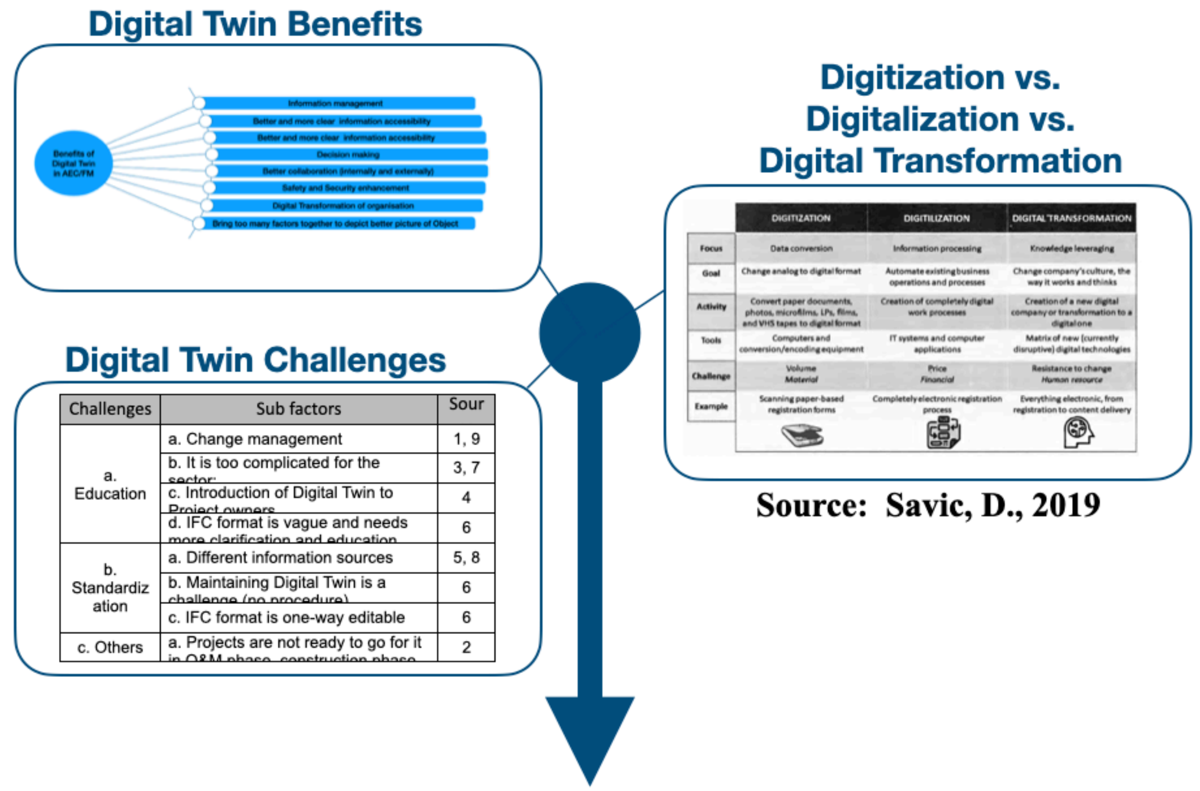
Comparing and combining table 4-3 (Digital Twin challenges drawn from empirical results) and figure 5-2 (benefits of Digital Twin) with figure 2-5 (comparison of Digitization, Digitalization and Digital Transformation) results in figure 5-3 that shows Digital Twin is part of Digital Transformation.

Focus, Goal, and activity shown in this figure, are the abstract of prior section, 5.2. benefits of Digital Twin. But to understand better that idea, reading prior section is recommended.

About challenges of Digital Twin, empirical results showed different challenges including people and resistance to change. Resistance to change was the key result that connected this thesis to the topic of Digital Transformation, something that is missing in literature. It is interesting that connection between Digital Twin and Digitalization is found in literature analyse by VOSViewer, see figure 3-2. But no Digital Transformation have been found in literature analyse.

Comparing "Digitalization" and "Digital Transformation", interview object 7 answers, 75% to 90% of IoT projects in UK failed. When we talk about smart assets, it means to connect asset to IoT sensor, that has been the reality of failure rate. S/He suggested going for smart assets and Digital Twin are not respective steps. We should define the goal/purpose of Digital Twin first.

Other challenges can be mentioned as (1) educational gaps between theory and practice, which is clearly visible in section 5.1. concept of Digital Twin; and (2) standardization, specifically for Digital Twin where we merge many factors together, unified information measures are critical.



	Digitalisation	Digital Transformation Digital Twin
Focus	Information processing	Knowledge leveraging **leverage knowledge of bringing many factors to a central system**
Goal	Automate existing business operations and processes	Change company's culture, the way it works and thinks **connecting Digital Tools to people and process**
Activity	Creation of completely digital work process	Creating a new digital company / process **better use of information and better collaboration**
Tools	IT systems and computer applications	Matrix of new (currently disruptive) digital technology **connecting all IT systems and applications to a unified platform**
Challenges	Price and financial barriers	Resistance to change (human resources) **people are willingness to change**
Example	Completely electronic registration process 	Everything electronic, from registration to content delivery **everything powered by computers, robots and AI; but still human is a part system** 

Figure 5-5-3: Digital Twin from Digital Transformation perspective (Own Creation)

In figure 5-3, "Digital Transformation" column includes black and blue texts. Black text comes directly from Savic, D., (2019); and blue text is regarding outcomes of this thesis.

And the final point, after considering mentioned challenges and solutions, it's worthy to consider Digital Twin not as an incremental, linear, concept. It's better to be considered as a living object (interview object 3). It's more about communication between technology, people, and process. We can start simple or even not perfect, then we learn by the time goes by. Also, many benefits of Digital Twin can emerge after a while. So, incremental classification of Digital Twin concept more limits its capabilities, specifically in figure 2-12 to FM-only purposes. While some other benefits and purposes can be achieved at the same time, like redesign, more sustainable design, construction purposes. Recommendation of this thesis is to view Digital Twin more like figure 5-4 bellow.

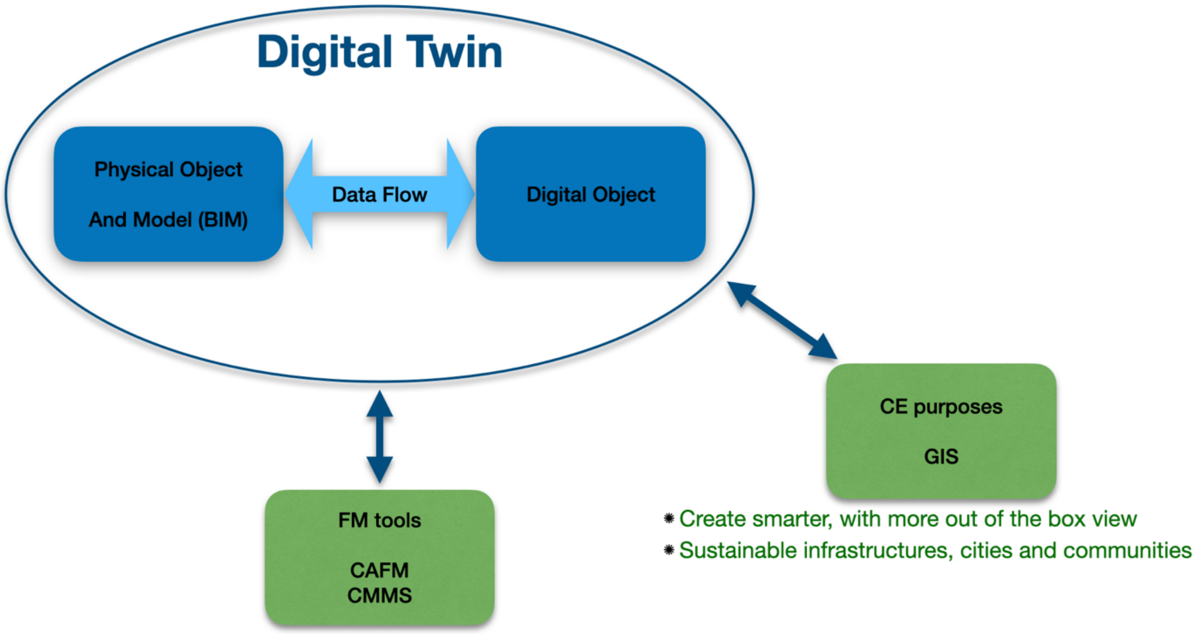


Figure 5-5-4: Digital Twin in a non-linear view (own creation)

To answer RQ1, after considering above mentioned points, to make a clear roadmap of Digital Twin to get to practice, to facilitate FM, following picture is created. Figure 5-5 defines focus area and questions need to be answered to implement Digital Twin.

Here are questions that need to be answered with some explanations:

1- How much information we need?

As interview object 1 mentioned, information is bloodline of FM. it's important to define enough input, not too little and not too many.
Some data can be used as they are collected, some other need to be processed.
some data can be general, some other data are very detail
all following questions should be answered separately for each information.

2- About information, what is the purpose?

Each data we collect can have a direct or indirect purposes. These need to be defined by practitioners in each sector (AEC) and can be different for each organization/project. Information links should be defined as well.

3- For how long we need to keep that data?

In Digital Twin we are dealing with huge amount of data. Efficient amount and duration of keeping information is an important measure that needs to be considered for better performance of system.

4- How frequently we need to update that data?

Answering to this question is different for different project phases. Construction phase is maybe 6 months while O&M phase can be several decades. So, this perspective needs to be considered when we are answering this question. Specially, handover between these two mentioned phases is a problem already in projects.

5- Update data automatically or manually?

IoT sensors are mentioned in literature as main source of data collection, but other tools like drone or 2D normal pictures can be also considered as data collection measures. Also, manual data collection also can be considered for some specific cases.

6- What standard do we follow?

Finally, standard is critical measure to be considered. Specially for Digital Twin that we combine and merge too many different parameters together.

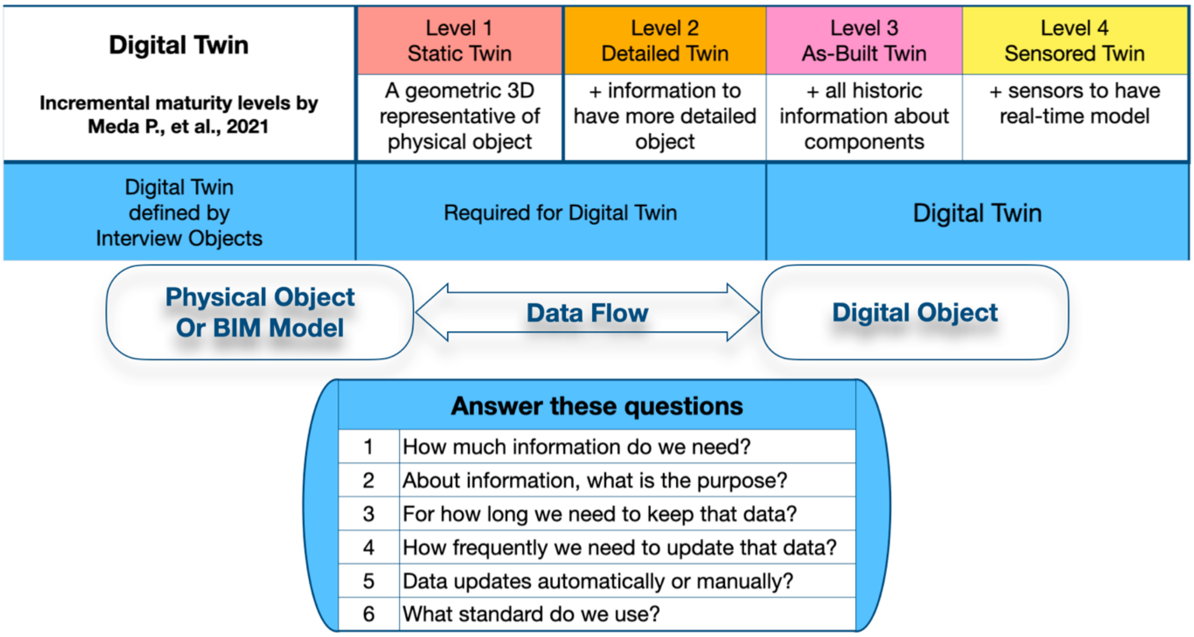


Figure 5-5-5: focus area of Digital Twin implementation (own creation)

6. Conclusion

Comparing Literature reviews and interviews with experts helped to answer research questions. And the most valuable outcome of this thesis is two findings bellow:

Fist conclusion is, something critical, that is missing in literature, and I believe is the main gap between theory and practice, is Digital Transformation which is underlying with Digital Twin concept. Most recent Digital Twin applications that have been found in literature, (Lu, Q., et al., 2022; Zhao, J., et al., 2022; Xie, X., et al., 2020) didn't mention Digital Transformation, neither in their literature review nor in their discussion. Also, we didn't find Digital Transformation concept to be mentioned in the literature reviews (Errandonea, I., 2020; Opoku, D.G.J., 2021).

Second conclusion is, almost all literatures mentioned Digital Twin with the power of AI and Machine Learning, to make smart asset management happen. While no interview object mentioned this point as direct outcome of Digital Twin. On the other hand, CAFM and CMMS, or other FM-tools are already available to facilitate FM in AEC. If Digital Twin is going to help that, Digital Twin needs to connect to FM-tools. Most interview objects mentioned that FM-tools should use Digital Twin data, but no literature have been found to try to connect Digital Twin with FM-tools.

Figure 6-1 includes two main conclusions. first conclusion, that is considering Digital Transformation, is before Digital Twin and depicted on top of the figure. In middle of that figure, first four levels of well-known Digital Twin maturity level are shown. To implement Digital Twin, answering 6 questions are required, which are shown down left of figure. To achieve best outcome for FM, we need to connect Digital Twin to a FM tool, that is shown in bottom right part, connection to FM-tools and AI are depicted to show roadmap of achieving best results of FM purposes in practice.

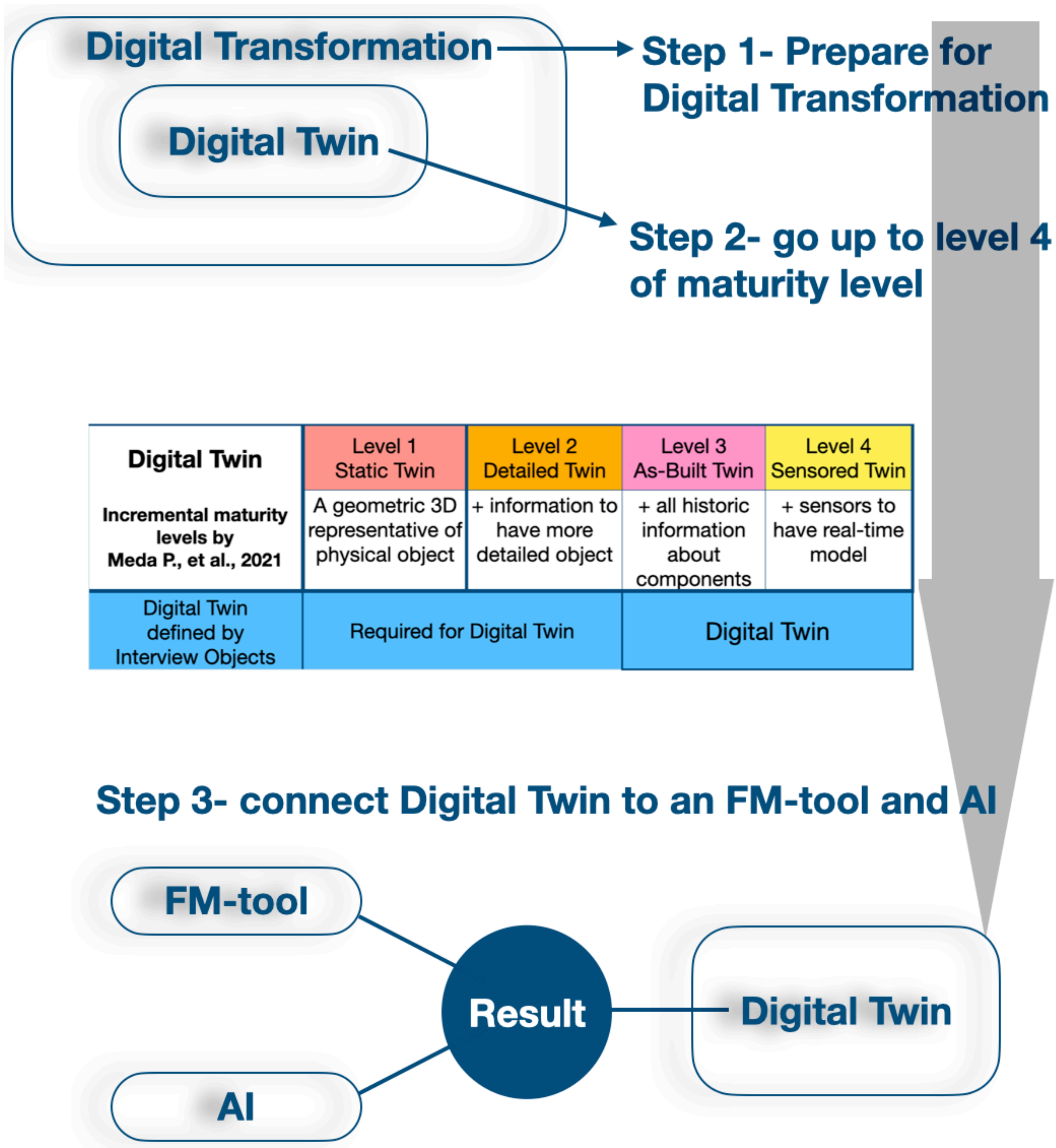


Figure 6-1: connecting Digital Twin to (1) Digital Transformation (2) FM-tool and AI (Own creation)

7. Future path

Two paths can be suggested for future studies.

1- Study Digital Twin from Digital Transformation perspective.

- Digital Transformation is a big topic, and it may lead to different strategies for each organization. In this regard, doing case study can be beneficial.

2- Investigate FM-tools and connect Digital Twin to them.

- maybe study DALUX-FM[11] software could be starting point as suggested by an interview object as a common FM software in Norway.

- Then power up the combination with AI.

[11] https://www.dalux.com/fm-overview/

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