VAASAN AMMATTIKORKEAKOULU
UNIVERSITY OF APPLIED SCIENCES

Amna Farid

DIGITAL TWIN IMPLICATIONS TO PROJECT DECISION-MAKING

Unit of Technology and Communication

2022

ACKNOWLEDGEMENTS

In the name of God Almighty who blessed me with this opportunity and guided me through the process and led me to my goal.

My sincere thanks to my thesis supervisor Dr. Adebayo Agbejule for his guidance and support throughout the process. He kept me motivated and was always there when needed. I would also like to thank Lotta Saarikoski for her help with arranging the interviews for the thesis.

I had the strongest support right by my side, my husband who gave me the courage to achieve my dreams and believed in me. My children have been supportive and understanding by allowing me to study and complete my thesis. Thank you, kiddos. And finally, my parents who are the source of my strength.

‘May the stay of human beings become more environmentally sustainable…’

VAASAN AMMATTIKORKEAKOULU
UNIVERSITY OF APPLIED SCIENCES
Ylempi ammattikorkeakoulututkinto, Projektinhallinta

TIIVISTELMÄ

Tekijä	Amna Farid
Opinnäytetyön nimi	Digital Twin Implications to Project Decision-Making
Vuosi	2023
Kieli	English
Ohjaja	Adebayo Agbejule

Digitaalisilla tekniikoilla on ratkaiseva rooli määriteltäessä toimialojemme tulevaa tilaa ja niiden ympäristöjalanjälkeä planeetallamme. Vaikka Architecture Engineering Construction Operation & Facility Management (AECO-FM) -projektit jättävät pitkäaikaisen vaikutuksen ympäristöömme, digitaaliteknologiaan perustuvat mahdollisuudet ovat merkittäviä. Muun muassa Digital Twin (DT) on yksi huipputeknologiasta, jolla on ominaisuuksia muuttaa AECO-FM-teollisuuden projektityötä ja joka voi lisätä projektin tulosten ympäristön kestävyyttä.

Tästä syystä tämän tutkimuksen tavoitteena on selvittää, kuinka tällaisten kykyjen käyttöönotto voi tukea päätöksentekoprosessia ja kuinka projektipäätökset voitaisiin tehdä järkeviksi eliminoimalla inhimillinen harha. Koska tällaisilla kyvyillä varustettu reaaliaikainen malli saa ihmiset keskittymään päätöksiin tehostetulla havainnolla ja parhaiden vaihtoehtojen toteuttamisessa AECO-FM-projektin elinkaari huomioon ottaen. Erityisesti tämä tutkimus tutkii Digital Twinin vaikutuksia projektien päätöksentekoon.

Tämä tutkimus hyödyntää tapaustutkimuksen tutkimusstrategiaa induktiivisen lähestymistavan avulla tietojen keräämiseksi kahdelta AECO-FM-alan tapausyritykseltä. Tiedot kerättiin puolistrukturoiduilla haastatteluilla (5), World Wide Webillä case-yritysprojekteista, case-yritysraporteilla ympäristön kestävän kehityksen tavoitteista ja strategioista sekä haastateltavien toimittamilla hankekohtaisilla asiakirjoilla. Aineiston kvalitatiivinen analyysi suoritettiin konstruktivistisella lähestymistavalla. Tutkimustulokset vahvistavat, että case-yritykset saavat ympäristön kestävyyden hyödyt auttamalla projektin päätöksentekoa digitaalisen kaksoiskappaleen kautta (i) tuomalla tietoa reaaliaikaisesti saataville, (ii) tekemällä ennustavaa analyysiä ja (iii) tarjoamalla datalähtöisiä parhaita vaihtoehtoja elinkaaren näkökulmasta. Tämä auttaa projektihenkilöstöä tekemään kokonaisvaltaisempia päätöksiä samalla kun ympäristön kestävyys asetetaan päätöksissä etusijalle. Samaan aikaan havainnot korostavat myös sitä, että DT-kypsyys on vielä alkuvaiheessa ja vaatii huomattavaa huomiota erityisesti yhteisten teknologioiden, alustojen ja toimialastandardien rakentamiseen AECO-FM-teollisuuden eri toimijoiden kesken.

Keywords Project Management, decision-making, digital twin, and sustainability.

VAASAN AMMATTIKORKEAKOULU
UNIVERSITY OF APPLIED SCIENCES
Master of Engineering in Project Management

ABSTRACT

Author	Amna Farid
Title	Digital Twin Implications to Project Decision-Making
Year	2023
Language	English
Pages	78
Name of Supervisor	Adebayo Agbejule

Digital technologies have a critical role in defining the future state of our industries and their environment footprint on our planet. While the Architecture Engineering Construction Operation & Facility Management (AECO-FM) projects leaves a long-lasting impact on our environment, the digital technology-driven opportunities are significant. Amongst others, Digital Twin (DT) is one cutting edge technology that has characteristics to transform AECO-FM industry project work, as well as could increase the environmental sustainability of the project outcomes.

Hence this research aims to explore how deploying such capabilities can support the decision-making process, and how project decisions could be made rational by eliminating human bias. Because the real-time model with such abilities will power the people to focus on the decisions with enhanced observation and implementing the best alternatives keeping in view the AECO-FM project’s lifecycle. Specially, this research explores implications of Digital Twin for project decision-making.

This research deploys case study research strategy with an inductive approach to collect data from two case companies in AECO-FM industry. Data was collected via semi-structured interviews (5), World Wide Web about case company projects, case company reports about environmental sustainability targets and strategies, as well as project-specific documents which were provided by the interviewees. The qualitative analysis of the data was conducted with a constructivist approach. The findings of the research confirm that case companies get the environmental sustainability benefits by assisting project decision making through digital twin (i) by making information available real time, (ii) conducting predictive analysis, and (iii) providing data-driven best alternatives with a lifecycle standpoint. This is helping the project personnel to make more holistic decisions while prioritizing environmental sustainability in the decisions. Meanwhile, findings also highlight that DT maturity is still in its early phase and needs considerable attention, especially, on building shared technologies, platforms, and industry standards between the different actors of AECO-FM industry.

Keywords Project Management, decision-making, digital twin, and sustainability.

TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

LIST OF ACRONYMS AND ABREVIATIONS

Acronym	Full form
DT	Digital Twin
DM	Digital Model
DS	Digital Shadow
AECO-FM	Architecture Engineering Construction Operation & Facility Management
BIM	Building Information Modelling
BAS	Building Automation System
BMS	Building Management System
IoT	Internet of Things
VR	Virtual Reality
AR	Augmented Reality
IFC	International Foundation Class
AIM	Asset Information Management
CDE	Common Data Environment
CMMS	Computerized Maintenance Management System
ESG	Environmental, Social and Governance
LCA	Life Cycle Assessment
CC	Case Company

1. INTRODUCTION

The adoption of digital technologies is a prominent driver for the sustainability of businesses, organizations, and societies (Boje et al., 2020; Yan et al.,2022). The impact of digital technologies is visible through the three phenomena: 1) World Wide Web and its adoption, 2) accelerated digital technology development and digital-competition, and 3) the consequential changes to the people's (consumer) behavior. Digital transformation has been divided into three phases Digitization, Digitalization and Digital Transformation (Verhoef, et al., 2021).

To keep up with the pace of digitization, organizations adapt to cutting-edge technologies, tools and systems as the key enablers of digital transformation, the Digital twin being one such promising technology (Kritzinger, et al., 2018) (Yan, et al., 2022). The Digital Twin utilizes data driven services that are based on diagnosis and predictive functions and thus support decision-making (Jürg, et al., 2021). Data is updated in real time from different sensors that run simulations for visual outcomes of possible context bound rational decisions. Such data driven inputs for project decision making is bringing exciting opportunities for businesses and environment (Bokhari & Myeong, 2022).

Projects are dynamic and organizations need to make the right decisions and that too at the right time. Decision-making is one of the important activities at every level of any organization. The decisions made at a strategic level of the organization sets the direction for the choices made at tactical and operational levels (Harrison, 1996). Hence, the process of decision-making at strategic and operational level gets connected and embedded in the organizations culture. Consequently, the strategic choices set a standard for implementing the actions, for example via environmental impact of infrastructure construction and facility management projects.

Decisions impacting the long-term environmental sustainability is a crucial challenge for AECO-FM industry (Bokhari & Myeong, 2022). The Digital

Twin brings new opportunities for AECO-FM industry. For example, controlling carbon emissions and improving energy efficiency is on the top of the list for constructing smart cities. To achieve the goals of carbon neutral buildings and energy efficient buildings, decision-making must be done from the conceptual phase of the projects to the decimation of the building infrastructures. Herein, the shared decisions made at operational, tactical, and strategic levels are crucial.

1.1 Research Gap

There is an opportunity to understand the decision-making process and use of modern technologies (Jürg, et al., 2021; Ozturk, 2021). The dynamics of decision-making, the process, and interdependencies of data in projects have been explained by Killen (2017). The importance of information availability and authenticity of the information has also been stressed upon. For example, the previous research shows that cognitive bias of project team members has great influence on decisions made within socio-economic settings (Acciarini, et al., 2021). Hence, Acciarini and co-authors (2021) proposed future research for *"focusing on the context of digitalization and on the role of big data, future research might explore the role of specific cognitive biases in each proposed decision-making process."* Therefore, the Digital Twin, with its abilities to handle big data, can offer a possible solution to eliminate cognitive bias from the decision-making process.

Architecture, Engineering, Construction, Operations and Facility Management (AECO-FM) projects consists of several multidisciplinary teams working together to achieve a common goal. There are many stakeholders involved and the decision-making process can get complex, cause delays and even disputes. Getting hold of the required information for timely decision making remains a challenge. This is a common cause of delays in construction projects resulting in cost overruns. Due to time shortage and limited data & information, the experts tend to take subjective decisions based on their experiences rather than being objective and rational as stated by (Khakheli & Morchiladze, 2015; Ksiazek, et al., 2015).

The Digital Twin is a new technology that is being adopted by the construction sector, so research is still novice on this topic. Recently researchers have started to write about Digital Twin capabilities in relation to engineering sector. There is room in research about many aspects of the Digital Twin and its relationship with project management; therefore, I found this topic very exciting for research. This study will focus on the on relationship of the Digital Twin and project decision-making and on how the new age technologies such as Digital Twin are impacting project decision-making.

1.2 Research Objective and Questions

This study will focus on the decision-making process, decision-making in construction projects and the Digital Twin supporting decision-making specially with reference to environmental sustainability leading to smart buildings and smart cities. The objective of this master's thesis research is to understand the impact of the Digital Twin as a digital transformation tool helping the case companies achieve their sustainability goals by supporting the project decision-making, as well that how project decision-making process evolved with the use of Digital Twin. The research focus of this thesis is presented in Figure 1.

Keeping the research gaps related to decision-making in the AECO-FM industry in mind and interest in the Digital Twin technology, two research questions were developed. Sustainability, being very close to my heart and a very big concern for today's human in every sector of life, was also made part of the research. Global warming and climate change have to be addressed by each and every responsible person.

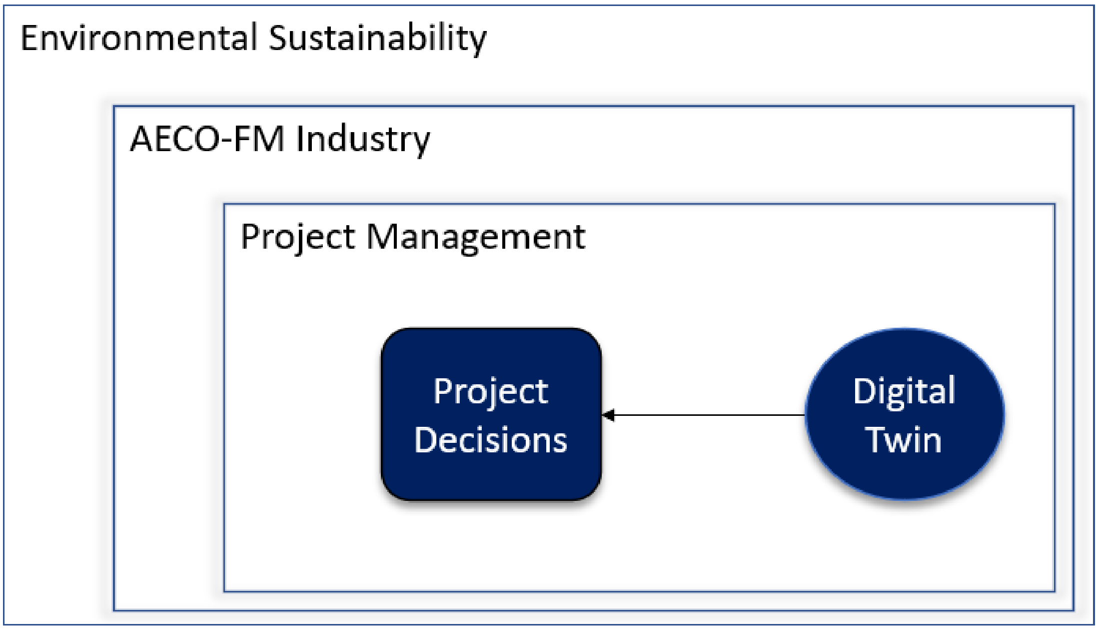

Figure 1. Focus of the research

RQ 1. How Digital Twin implementation supports project decision-making?

RQ 2. How Digital Twin helps to achieve sustainability goals through project decision-making?

After going through the literature related to the research topic and research questions, a framework was developed for data collection during the semi-structured interviews which is explained in section 2.3 (Figure 12).

1.3 Thesis Structure

This thesis report consists of six chapters and a reference section (Figure 2). Research introduction, research gap and the objective of this research are discussed in Chapter 1. This chapter also states the research questions and the research framework for the data collection, analysis, and presentation of the case findings.

Chapter 2 is dedicated to the literature review on the topics of the research. The literature review was done keeping the research questions in mind to develop a sound understanding of the concept of the Digital Twin, the decision-making process, and how environmental sustainability is related to these topics. The main source of literature was from scientific journals, the prominent examples include International *Journal of Project Management*, *Management Decisions*, *Managing Projects in Business*, *Automation in Construction* and *Strategic Management Journal*. The articles were searched with keywords such as Digital Twin, decision-making, and sustainability in AECO-FM. Then the references for the shortlisted articles were gone through to find more relevant articles.

Chapter 3 presents the research methodology used for this research. It explains why the qualitative case study method was selected for this research: why inductive research suited this research and how was the process undertaken. Two case companies were selected, and semi-structured interviews were conducted for data collection. Data was also collected through other means, such as from reports and case companies websites.

In Chapter 4, the collected raw data was structured into patterns and observations that can be generalized to give an overall view of the research topic in practical field. Chapter 5 explains the relation between the findings from the case companies and the literature review. Chapter 6 gives the conclusions derived from the research, states the limitations and recommendations for future research.

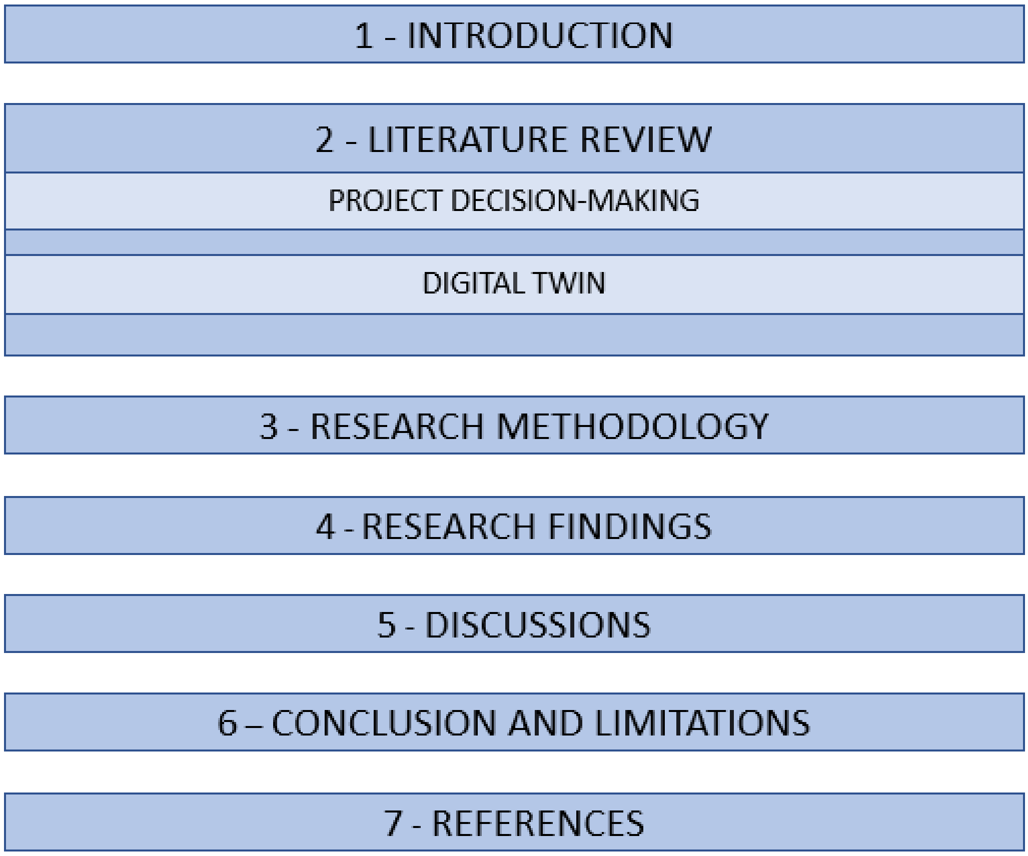

Figure 2. Thesis Structure

2. LITERATURE REVIEW

Projects are considered as temporary organizations aimed to achieve a defined goal or target, in line with the organization's strategy with a specified budget, scope and within time limit. These specified scope cost and time are commonly known as the triple constraints. Projects are unique in nature, meaning the environmental and social factors related to every project are different. Projects are successful if they meet the three set criteria. Project management is the means by which the specified scope, time and cost are planned, managed, and controlled to deliver the set goals (Kerzner, 2013).

According to Le, et al., (2018) the AECO Project lifecycle can be divided into 6 phases (Figure 3). Construction projects are very complex in nature as there are many different parties involved during the execution. There are several stakeholders and experts involved responsible for decision-making during all the phases of the project.

1) Project initiation
2) Project design & planning
3) Project procurement
4) Project construction /execution
5) Project maintenance
6) Project closure

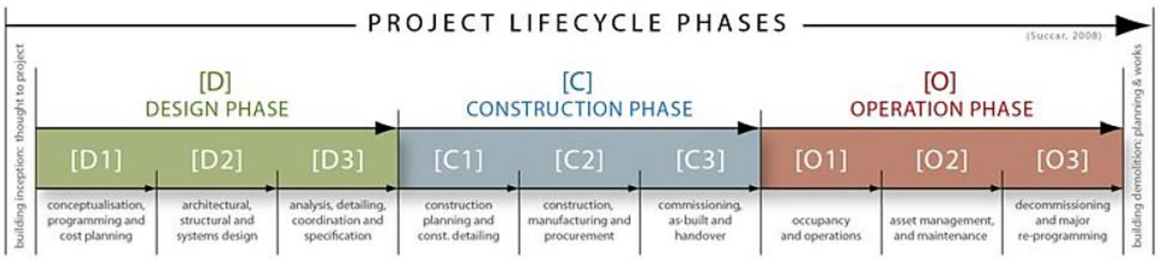

Figure 3. Project Phases as presented on website (BIM framework, 2020)

Project management starts from the ideation of the project and continues throughout the lifecycle of the project. Every phase of the project has some processes unique to it and there are some that are present throughout the lifecycle, decision-making being one of them (Kerzner, 2013). According to Nahyan et al (2019) there are four major management processes in construction projects namely communication, coordination, decision-making, and knowledge-sharing. Quite a lot of research has been done on the communication, coordination and knowledge sharing processes of project management but there is a gap in the research of decision-making. According to Hwang & Ng (2013), decision-making scored highest skill required by project managers to deliver green construction projects.

2.1 Project Decision-making

A decision has been defined as a choice of a course of action from the available options. It cannot be a decision if there is just one option. Decisions are more complicated in the construction industry due to some specific conditions (Szafranko, 2017). Decision and behavior are stated as the two core characteristics for the decision-making phenomena by (Oliveira, 2007).

According to Müller (2009) decision-making is *"a cognitive phenomenon and conceptualized as the goal or end point for a more or less complex process of deliberation, which includes an assessment of consequences and uncertainties*".

As per the theory of decisions by Edwards (1954), it is important to understand the three assumptions about a decision-maker:

1) *"…is completely informed,*
2) *…is infinitely sensitive,*
3) *…is rational*".

Rational decision-making theory was developed prior to the Second World War in the normative style by the industrial engineers, specialists in business functions and people involved in digital innovation belonging to management sciences. The theory developed in management sciences has a common concern with the "ways" in which decisions are made and not just the outcomes. These theories are concerned with "how to decide" rather than "what to decide" (Simon, 1979). Based on the data in Edwards (1954) and Simon (1979) the following figure was developed which shows the evolution of present-day Rational decision-making theory and Behavioural decision-making theory from the Economic theory (Figure 4). Economic theory was the foundation theory from which two school of thoughts originated the Descriptive and the Normative as described in the following paragraph.

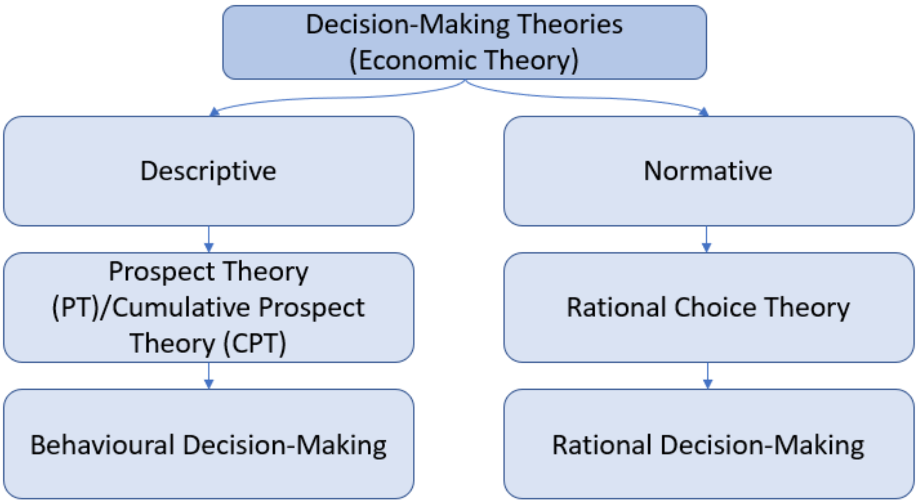

Figure 4. Decision-making Theories from Edwards (1954) and Simon (1979)

The decision-making process considers multiple factors and multi-dimensions while processing information. To enforce strict models without situation specific dynamic, quantitative and qualitative data raises questions implying that the descriptive theory has its limitations (Nwogugu, 2005). Descriptive or behavioural decision theory focuses on how decision makers process information and interpret their environments and decide while normative or rational theory focuses on how decision makers should decide and establish a weightage mechanism between the alternatives and its value. Be it the descriptive or the normative theory all theories conceptualize the values, beliefs, and behaviour (Oliveira, 2007).

Decision-making is a phenomenon in which several factors are to be considered and it requires time. Decision-making requires capabilities, such as critical thinking, keen observation, logical reasoning, vision, time management and emotional intelligence. The barriers in decision-making are lack of complete and authentic information, personal biases, and time limitation (Secundo, et al., 2022). In projects managers must make decisions based on massive volumes of information and limited time (Killen, 2017). So, the managers do not have enough time to absorb all the information required to make rational and objective decisions but rather they opt for subjective decisions, this is very common in construction projects.

A visualization framework for project decision-making considering all the related aspects can be as follows expanded from Secundo, et al. (2022)

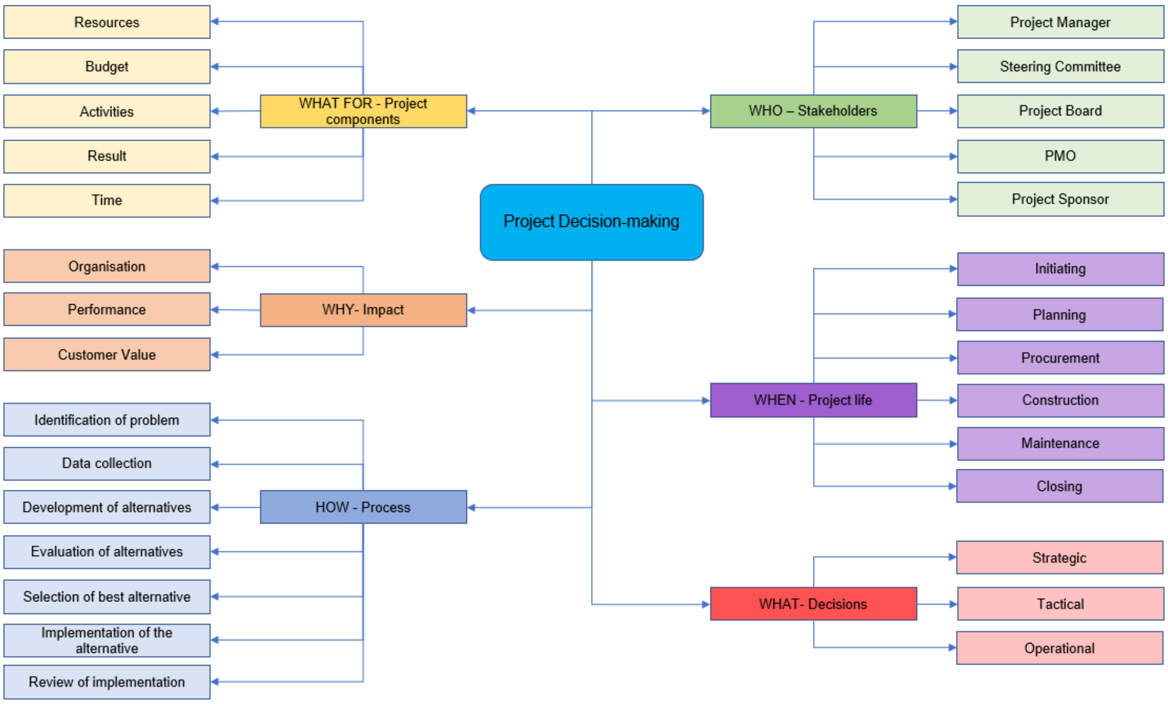

Figure 5. Project framework adopted from Secundo (2022)

According to Khakheli & Morchiladze,(2015) and Nahyan, et al., (2019) there are many factors that determine the decision-making such as

- Leadership style
- Stakeholder influence and management
- Organizational culture
- Environment (risk and uncertainty, time factor etc.)

Oliveira, (2007) has brought in the aspect of culture to decision-making as organizations tend to develop a cultural-ethical decision-making model.

Stingl & Geraldi (2017) conducted a systematic literature review about behavioural decision-making and grouped the research into three school of thoughts namely Reductionist, Pluralist and Contextualist (Table 1). This present research is closer to the reductionist school of thought as it focuses on rational decision-making and considers bounded rationality and cognitive biases as factors affecting decision-making process and how deviations from rationality mitigated.

Table 1. Systematic Literature review extended by Stingl & Geraldi (2017) from Powell et al. (2011)

	Reductionist	Pluralist	Contextualist
Ontology in relation to decisions	Decisions should be rational, and deviations from rationality should be mitigated.	Decisions are negotiation arenas, prone for conflict of interests, bargaining and opportunistic behaviour.	Decisions are sensemaking processes, intertwined in the negotiation of meaning before, during and even after the project.
Assumptions about decision maker's behaviour	Decision makers (or groups of decision makers) make decisions consciously as 'events' but are bounded-rational, and hence cognitively limited.	Decision makers are rational and strongly influenced by personal and political interests, which can be in conflict with that of the project.	Decision makers do not 'make' decisions, but are actors constructing narratives which will shape processes of attention, prioritization and ultimately decisions.
Core processes of interest	Individual and intragroup decision making	Intergroup bargaining, problem solving, politics, conflict resolution, organizational learning, resource allocation	Sensemaking, perception, enactment, action generation
Caricature of project actors portrayed in research findings	The optimist: project actors suffer from pronounced optimism bias	The opportunist: project actors have their own interests at heart	The orchestrator: project actors surf on waves of meaning, in an highly ambiguous world
Key generic concepts in social and cognitive psychology	Cognitive biases; heuristics; bounded rationality; subjective utility/probability; personality types, groupthink	Conflict culture; decision process (inclusion/participation); intra-project communication; negotiations/bargaining; game theory	Culture (Hofstede model), language, signs & symbols, values, taboos, sensemaking, storytelling, future perfect strategising
Typical methodologies	Positivist research, marked by experimental research, modelling and simulation	Critical realist, socio constructivist, marked by qualitative and multi-method tradition.	Socio constructivist, marked by qualitative, in-depth studies, ethnography, grounded theorizing.
Examples of classic contributors	Edwards, Simon, Von Neumann-Morgenstern, Tversky-Kahneman, Schelling, Bazerman, Loewenstein, Lovallo	March, Cyert, Simon, Fiske-Taylor, Bower, Miller, Kets de Vries, Hambrick, Levinthal, Denrell, Bromiley, Rumelt, Winter	Weick, Starbuck, Pettigrew, Brunsson, March, Staw, Mintzberg, Abrahamson, Reger, Huff, Fiol, Milliken, Hodgkinson, Bettis, Mitroff
Examples of contributors from project studies	Flyvbjerg, Jani, Keil, Shore, Martinsuo, Kutsch, Hällgren, Williams	Flyvbjerg, Pinto, Kujala, Clegg, Winch, Chapman, Mullaly	Pitsis, Alderman, Musca, Winch

According to Kerzner (2013), project decisions are made at three major levels: Strategic, Tactical, and Operational.

Strategic decisions are executive-level decisions and non-programmed and complex in nature. Strategic decisions are long term oriented and direct the organization’s path towards its set goal. These are high risk and high-stake decisions. They rely on information, analysis, experience, and vision.

Tactical decisions translate strategic decisions into action. These are less complex and more straightforward than strategic decisions. These decisions are taken by the middle management and are semi-structured. If the tactical decisions are also in line with the organization’s strategy, then it adds to the value of the outcomes.

Operational decisions on the other hand are more programmed and repetitive in nature. These are day to day task-based decisions and are usually made following some set criteria, such as organizations procedures and processes. Operational decisions are frontline decisions made on daily basis. As these are programmed decisions so they hold less risk strategically but can hold high risk for health and safety scenarios (Khakheli & Morchiladze, 2015) (Kerzner, 2013).

2.1.1 Project Decision Categories

Some decisions are easy to make while some are very complex and need teams of experts. Anybody can make a decision but making the right decision is the hard part. There are a lot of tools and techniques that can be utilized but which tool to use also depends on the type of decision (Kerzner, 2013). There are majorly our categories of decisions namely Routine decisions, Adaptive decisions, Innovative decisions, and Pressured decisions.

Routine decisions are the common day to day life decisions and are usually made by the project manager. These are simple and straight forward, such as selecting vendors, and authorizing overtime. These decisions are usually based on policies and procedures. Routine decisions are simple but the number of decisions to be made can become troublesome so they can be delegated to the project team (Kerzner, 2013).

Adaptive decision making is most common in projects. This type requires intuition to some extent. The problem is simple, and the project team is usually able to make the decision without any outside help. Special tools and techniques are also not required (Kerzner, 2013).

Innovative decisions are the most complicated ones in the projects as they refer to something new and are most often used in R&D projects. These decisions involve experts that may not be part of the project team. These decisions may also require use of advanced decision-making tools and techniques. The success of innovation adds great value to the organization on the contrary its failure can cause negative effects on the team as well as the organization. So, these decisions are hard to make and require a lot of time and competence (Kerzner, 2013).

Time is one of the triple constraints of every project and can have substantial impact on the decisions. The time required to understand the problem and find the right solution may require more time than what is available, so in these situations the decision must be made based on the available time. High pressured decision-making can be part of adaptive and innovative decision types as well making them more difficult. Often pressured decisions lead to suboptimal outcomes (Kerzner, 2013).

Decisions can also be generally divided into **programmed** and **non-programmed** decisions. Programmed decisions are about the routine tasks and repetitive in nature, while non-programmed decisions are more unique in nature and made in difficult situations; they provide problem solving and innovative solutions (Khakheli & Morchiladze, 2015)

2.1.2 Decision-making Styles

There are several decision-making styles. The style of decision-making also depends upon the situation and circumstances. For example, logical decision-making is most used as it provides with informed decisions but in case of time limitation intuitive decisions are also made. Some common decision-making styles are namely Command, Consultative, Group consensus, and Delegating styles.

In command style the leaders make the decisions on their own. They are solely responsible for the decision and its outcome. In some cases, it is needed but this style often creates lack of commitment to the decision. The team feels disconnected and motivation levels tend to drop.

In consultative style the leader makes the final decision but takes advice from the team. So, the team feels part of the decision process. The team feels more committed to the decision as compared to command style.

In group consensus style every member of the team takes part, and the decision is made by the team, the leader guides the team towards the decision. The team is fully committed to the decision as they have been part of the process and the decision is made with everyone's agreement.

In delegating style, the leader transfers the responsibility of decision-making to a team member. It is not very common and can cause tense environment among the team members.

Each person has their own style of decision-making, and it may be different than the team members. So, the person in authority should be able to evaluate the situation and circumstances so that he can make the right decision at the right time and that too in the right manner. T Table 2 taken from PMI webpage explains different styles of decision making (Kirytopoulos, et al., 2010)

Table 2. Styles of Decision-making

Name	Description	Advantages	Disadvantages	When to use
Command style	The leader decides on his/her own. May ask the members of the group about specific technical issues.	the decision is made quickly	the group members have little or no commitment to the decision	▪ the group perceives the leader to be the expert, ▪ the group likes all of the possible decisions, ▪ the group asks the leader to decide ▪ it is not important that the group be committed to the decision ▪ there is not enough time (e.g., in a crisis situation).
Consultative style	The leader decides on his/her own. Takes advice from the group before making the final decision.	the decision is more likely to meet the needs of the group than with the command style	some or all of the group members may still disagree with the decision that has been made	▪ the group does not have the information, education, skills, or experience to make a high quality decision, ▪ the group does not share the same goals or objectives that the leader hopes to achieve by solving the problem.
Consensus style	The group decides. The leader acts as a guide to the group.	high degree commitment to the decision by all members of the group, as they are actively involved in the process and all of their interests are addressed	the time required to make a decision and the associated costs of people's time	▪ the group shares the same goals or objectives that the leader hopes to achieve by solving the problem ▪ the group members have the education, skills, and experience to make a high quality decision, ▪ it is important that the group have a high degree of commitment to the decision reached, ▪ there is time available to use this style
Majority vote	The group decides. The leader acts as a facilitator to the group.	simple and intuitive, brings quickly large numbers of people in on a single decision with minimal cost	can lead to a "tyranny of the majority, a group may vote for other purposes than to resolve a substantive issue, little responsibility	▪ there is no expertise needed for the decision (simple/minor decision) ▪ there is a need to include a large number of people at relatively low cost ▪ there is not enough time

2.1.3 Decision-making Process

Decision-making can be intuitive, reasoning-based, or rational. Intuitive decisions are based on gut feeling and cannot be completely rejected, as heart always tells the truth. Reasoning-based decisions are discussion based and involve mutual agreement of the group. This process is time taking and requires experience and knowledge for reasoning. Rational decision-making is very efficient and effective (Khakheli & Morchiladze, 2015). As described in section 2.1, rational decision-making is based on the normative style and the economic theory. To make sure decisions move from bounded rationality to rational decisions a process is developed and that helps in achieving the desired results. This research will focus on this type of decision-making.

Traditionally data driven or rational decision-making process is divided into 7 steps (Figure 6).

1. Identification of problem
2. Analysis of problem, data collection.
3. Development of alternatives
4. Evaluation of alternatives
5. Selection of best alternative
6. Implementation of the alternative
7. Review of implementation

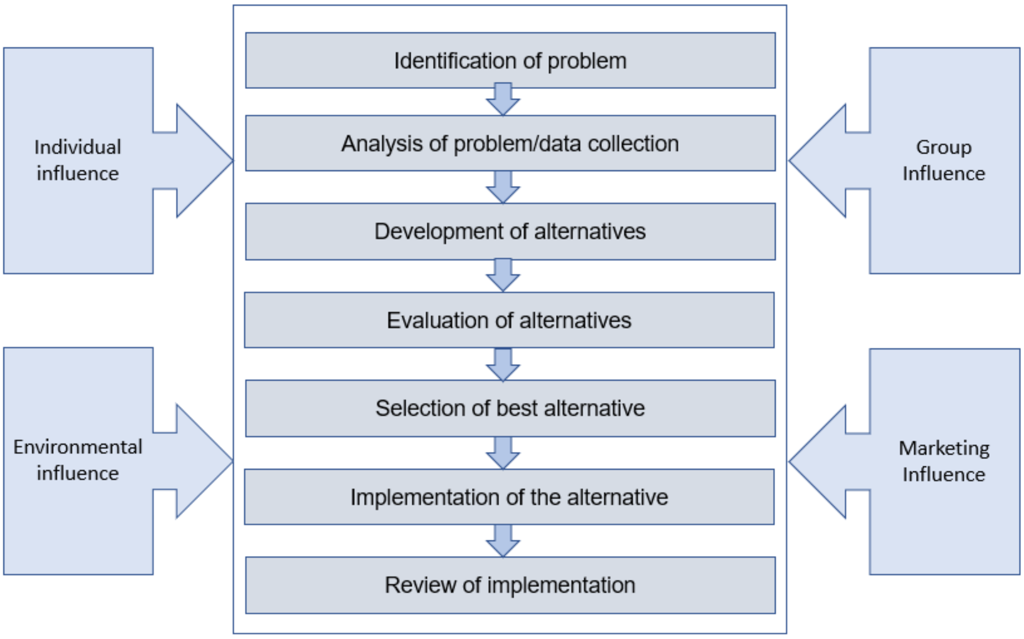

Figure 6. Data Driven decision-making process.

The process starts by the identification of a problem that needs to be solved, and the decision-making style that works with it. Limits and criteria need to be set and clear. Then the generation of ideas takes place and eligible ideas are then assessed based on the set criteria. The best option is then selected and implemented. Finally, the review is done on the implemented option answering the question that “did we receive the planned results and were the goals met?” (Khakheli & Morchiladze, 2015).

Decision-making activities can be more time consuming and costly than the problem-solving activities, as there are several alternatives to be identified, evaluated, and prioritized (Kerzner, 2013) (Khakheli & Morchiladze, 2015). Data driven decision-making process has been explained by Harjit Singh in his book in detail as in Figure 7.

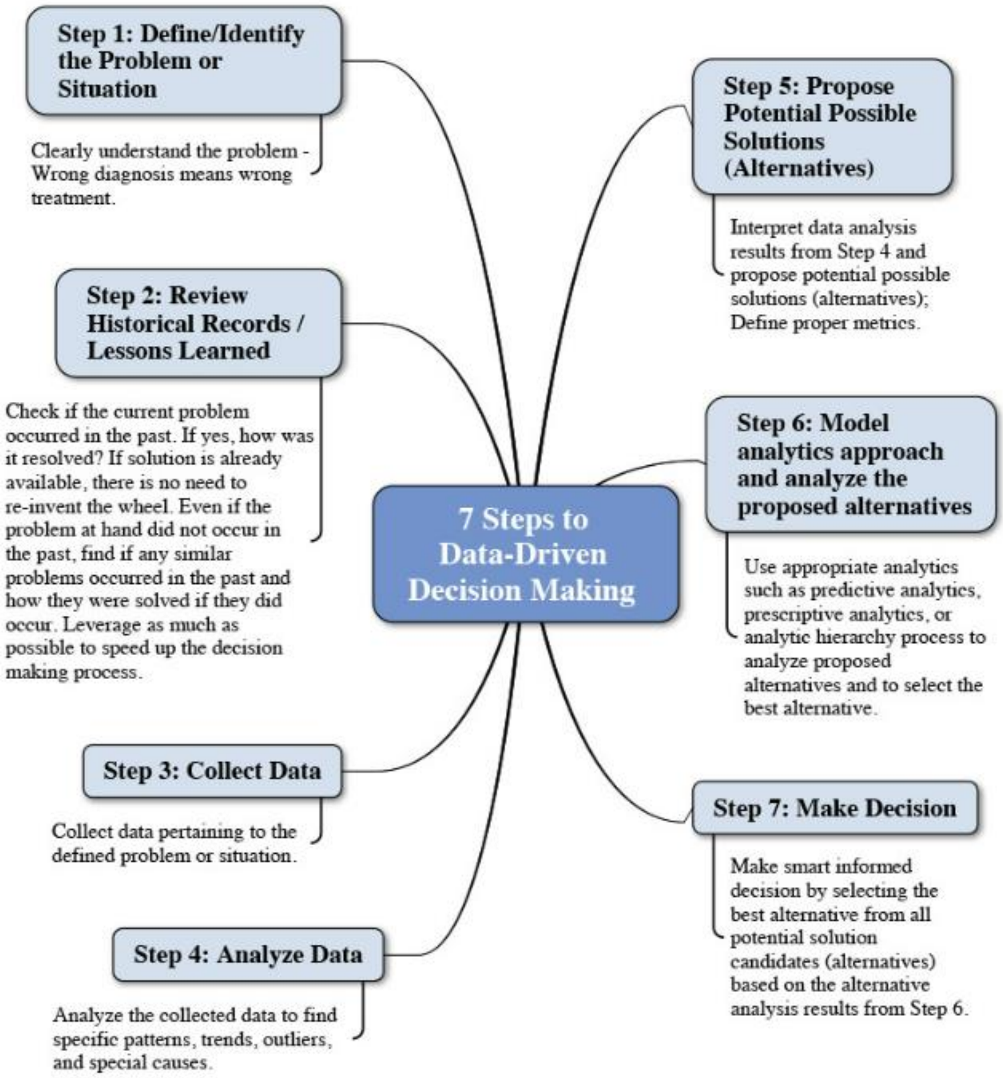

Figure 7. Data driven decision-making (Singh, 2015)

2.1.4 Data and Information for Project Decision-making

The role of quality of information available for the process of decision-making is of great importance and has been asserted upon by researchers. In any decision-making process the first step is the identification of a problem or opportunity and then the information available about that issue. Here the quality and reliability of the information is of utmost importance. This information will lead to the options and selection of a decision (Citroen & L., 2011). In a rational decision-making process or data driven decision-making the information required is important as it will direct the process. The first important thing is which information is needed and how to acquire it and then the authenticity of that information. The time limit is crucial here, this has to be done within the available time period. The technological advancements of AI and IoT bring their value at this point. Digital Twin using knowledge that is being constantly updated from multiple sources helps in selecting the best criteria for decision-making (Jürg, et al., 2021). Common knowledge is the key factor for shared decision-making (Weck, et al., 2022).

2.1.5 Visualizations for Decision-making

Knowledge visualization and representation of the authentic information is necessary for decision-making. Visualization is a way in which raw data and the available information can be made accessible in an understandable way for the users. (Yan, et al., 2022) The dependencies and the interdependencies of the projects also impact the decisions and should be considered and understood. Visualization helps in providing a clear picture of these (Killen & Kjaer, 2012). Knowledge visualizations helps in reducing cognitive biases due to complexity and uncertainty and helps in decision-making (Secundo, et al., 2022) (Acciarini, et al., 2021).

To visualize project management-specific information tools have been developed that are categorized as Visual Thinking Tools that help the team members to develop a common ground for concept mapping and development for example, concept maps and storyboards, Visual Project Reporting Tools that help the teams in analysing and summarizing key performance metrics for example , dashboard and Kanban boards, and Visual Project Collaboration Tools that help collaboration among team members and stakeholders for example , project display wall and project social media (Secundo, et al., 2022).

According to Killen, et al. (2020) further research is to be done on how to identify and visualize different sources of data that can support project managers in making critical decisions. The Digital Twin uses information in the form of knowledge visualization. The Digital Twin is updated in real time from different sensors, and it uses those to run simulations for the possible options and show visual outcomes making it easier to make the decision (Jürg, et al., 2021).

2.1.6 Decision-making in AECO-FM Industry

Decision-making is critical for the success of any construction project. Decisions must be made on daily basis and every wrong decision adds to the cost and time overrun which are very common problems of construction projects. Experts have to make decisions on daily basis, and they must be able to justify their decisions as well. (Poon & Price, 1999) (Nahyan, et al., 2019).

One of the most difficult problems in the AECO-FM industry is taking objective or rational decisions. As it has been established in research that decision-making process is complex and requires a lot of time, experts tend to take subjective decisions (intuitive and reason-based) based on their experience and knowledge (Ksiazek, et al., 2015) (Khakheli & Morchiladze, 2015).

In the construction industry stakeholder attributes, behaviour and management plays an important role in decision-making (Yang, et al., 2014). Multi criteria decision-making 9 stage model was proposed by (Erdogan, et al., 2017) where he states that the criteria for the alternative's selection should be set, and their evaluation should be defined and standardized. To support objective decision-making in construction projects (Ksiazek, et al.,

2015) proposed an informatics tool called ESORD that ranks solutions based on mathematical calculations.

Delays, time overruns, and cost overrun are very common in construction projects and one of the major reasons for that is the delayed decisions by the clients (Nahyan, et al., 2019). According to (Poon & Price, 1999) experience and knowledge were the main contributing factors for decision-making. Most of the decisions produced satisfactory results and could have been improved if there was more time and by acquiring relevant information. Most importantly 40% of decisions could have been avoided by adequate preparatory work, complete design, better coordination, and better planning. Based on the literature review following decisions were listed and divided into project phases and levels (

Table **3**).

Table 3. Project Decisions

Project phase	Decisions		
	Strategic	Tactical	Operational
Initiation	• Go / no go. • scope		
Planning	• Cost estimation • Tenders • Resource allocation • Communication routine • Stakeholder management	• risks • Tools & applications selection • Scheduling	• Design details • Reporting
Procurement	• Supplier selection	• Production planning	• Construction logistics

Execution / construction	• Environmental issues (co2 emissions • Cost management	• Safety management • Quality control	• Site monitoring • Site layout • Material management • Construction methods • Workforce safety
Maintenance	• Life cycle costing	• Quality control	• Check-ups • HVAC control • Energy consumption
Closure	• Demolition of the project		

2.1.7 Sustainability in AECO_FM Industry

The aspect of sustainability is becoming important day by day and should also be considered during the process of decision-making (Silvius, et al., 2017). In his paper Silvius (2017) says that sustainability of natural resources date quite back but the concept of sustainability in project management is newer. It is gaining importance with the current global conditions. So, he states that sustainability should be considered in addition to cost, time, quality, and risk aspects for project decision-making. Nowadays smart building and smart cities construction is the new trend towards sustainability.

If we look at smart buildings, the first question that comes to our minds is what a smart building is. What makes a building smart is the use of technology to enable efficient and economical use of resources and creating a safe and comfortable environment for the occupants. Smart buildings have been defined by Everett as follows:

“A dynamic and responsive architecture that provides every occupant with productive, cost effective and environmentally approved conditions through continuous interaction among its four basic elements: places (fabric; structure; facilities); processes (automation; control; systems) people (services; users) and management (maintenance; performance) and the interrelation between them." quoted by (Everett, 2009).

There are three main aspects of sustainability namely economic, social, and environmental. According to Silvius, et al. (2017) Table 4 shows dimensions of sustainability in research. In the AECO-FM industry the concept of sustainability is not new but in the past few years it has gained more importance and its consideration has become a part of the process.

With the real time, dynamic data of the assets we can optimize the environmental conditions so that user satisfaction and human well-being can be improved. In other words, DT provides us more control over the environment where we live and work (Brilakis & Hans Fischer, 2019). Buildings have an impact on the users /humans who occupy them. Indoor air quality, thermal comfort, acoustics, and lighting are all connected to user health and productivity. Optimal and informed decisions lead to sustainable construction that meets social, environmental, and economic benefits such as improved living conditions, conserving resources, reducing operating costs and increasing user satisfaction (Pearce, et al., 2010).

Table 4. Dimensions of Sustainability adopted from (Silvius, et al., 2017)

Principles/Dimensions of Sustainability	Seminal sources
Sustainability is about balancing or harmonizing social, environmental, and economic interests	Elkington (1997)
Sustainability is about both short-term and long-term orientation	Meadows et al. (1972), World Commission on Environment and Development (1987).

Sustainability is about both local and global orientation	Hurrell and Kingsbury (1992)
Sustainability is about values and ethics	International Organization for standardization (2010), Gareis et al. (2013)
Sustainability is about transparency and accountability	International Organization for standardization (2010)
Sustainability is about stakeholder orientation	Freeman (1984)
Sustainability is about reducing risks	Godfrey et al. (2009)
Sustainability is about eliminating waste**.**	Braungart and McDonough (2002)
Sustainability is about consuming income, not capital	Dyllick and Hockerts (2002)

Climate change is a big concern of our times and EU has also adopted a target of limiting the temperature rise below 2.0 Centigrade. Finland has set its carbon neutral goals for 2030. And to achieve this the AECO-FM sector needs to play its part as buildings account for over one third of all the greenhouse gas emissions. Buildings have a 30 to 40 % part in the Finnish carbon footprint. Out of which 90% is from life cycle emissions and almost 10% from construction phase. Even the emissions in the construction phase seems less but they are significant as they are released relatively in a short time phase (Säynäjoki, et al., 2011).

2.2 Digital Twin (DT)

Digital Twin (DT) is the virtual replica of a physical entity, e.g. buildings, products, and even human objects. The Digital Twin can be defined in a variety of ways for different industrial fields. *"A Digital Twin is a synchronized instance of a digital template or model representing an entity in its life cycle and is sufficient to meet the requirements of a set of use cases."* (Nath, et al., 2021). The starting point for a need of a digital twin is that it gives the same information that we get while physically being present at a certain location at a certain time, it provides the opportunity to go through the what -if scenarios. (Nath, et al., 2021)

Digital Twin is built using the **Digital thread** which refers to the communication framework that allows the data to flow from the physical world to the virtual replica throughout the lifespan of a product in real time. While separate Digital twin can be developed for different phases of a single product (Nath, et al., 2021). These digital twins can be for different purposes like for planning, monitoring, decision-making etc.

Digital model, Digital shadow and Digital Twin as explained below are all virtual representations of the physical assets but can be distinguished by the data flows and level of data integration (Kritzinger, et al., 2018) (**Figure 8**).

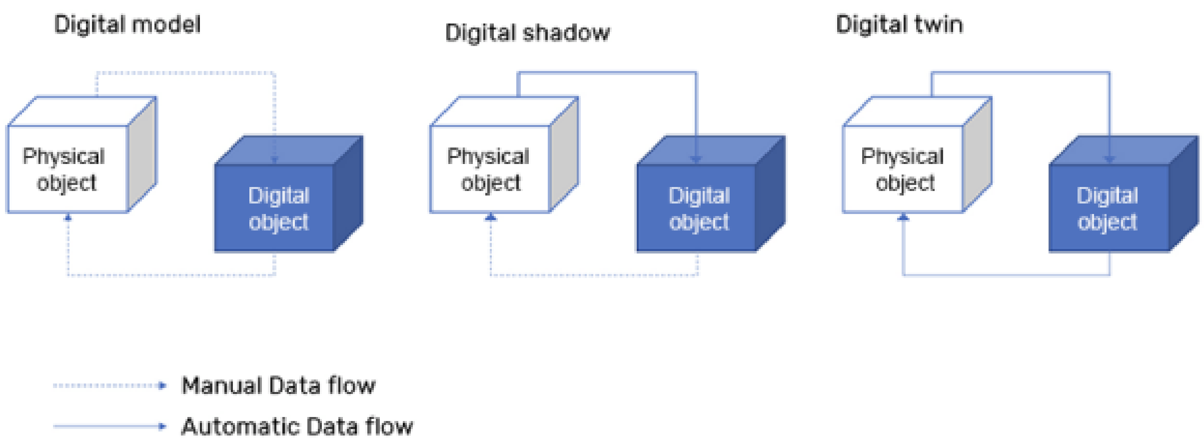

Figure 8. Data flow for DM, DS, and DT (CADMATIC,2020)

Digital Model (DM) refers to a 3D model that does not automatically link to a physical asset. Any modifications to the physical asset require manual entry to the virtual copy. In context of the AECO-FM industry older BIM models it can be such examples where only manual data entry was possible. And the data flow is unidirectional. The data is mostly manually handled in the format of PDF's and is static in nature.

Digital Shadow (DS) represents a level of maturity in which the model only allows one- way automatic data flow, from the physical asset to the virtual representation. However, it is limited in its ability to allow data flow from virtual to physical asset. This model still lacks the ability to interpret data and provide corresponding solutions.

Digital Twin (DT) In contrast to DM and DS, DT is characterised by bi-directional real time data flow facilitated by sensors and IoT technology. This allows continuous and accurate representation of the physical asset. Bi-directional data flow refers to the ability of data to flow in both directions, from the physical asset to the virtual model and back from the virtual model to the physical asset (Boje, et al., 2020). This concept has been employed in the manufacturing industry but is new in construction industry.

The term **Digital Twin** was first used by the National Aeronautics and Space Administration (NASA) in their Apollo program in the 70s. Then after many years this term has come up from the early 2000 and is gaining hype with every passing day (Hu, et al., 2021). Hu says, since 2016 digital Twin has been recognized as one of the top technological trends with strategic value. Digital Twin is the combination of BIM, IOT and Data management. Digital Twin is defined in variety of ways for specific fields. No one definition fits all.

2.2.1 Digital Twin and the AECO-FM Industry

According to (Ozturk, 2021; Shahzad, et al., 2022) Digital Twin is a vast technology, and it can be used to support the design, construction, and operations phase of the built assets. It is developed with specific facilities and purposes in mind. A digital Twin can be developed of a single asset (building) and or of a city. It can be just for the asset management, or it can be for the whole life cycle of the built asset, be it a single building or a city. So, before developing Digital Twin the purpose should be clear.

In the AECO-FM industry context Digital Twin is as "*A digital twin is a digital replica of a physical built asset. What a digital twin should contain and how it represents the physical asset are determined by its purpose. It should be* *updated regularly in order to represent the current condition of the physical asset. A digital twin should be standardised yet extensible, able to address key use cases directly and specialty use cases with extensions, cloud and computationally friendly, scalable and verifiable*." (Brilakis & Hans Fischer, 2019)

Digital Twin's concept is comparatively new in the AECO-FM Industry. The new age trends of digitalization and digital transformation have also started in this industry leading to the concept of smart buildings and smart cities. This concept is also being applied to the life cycle management. The virtual replica of the physical asset and its continuous monitoring can help in redefining the industry. The systems being used like BIM can be integrated with the DT technology and the industry can benefit in improving the efficiency of the processes. With the help of DT and an integrated system all the different stakeholders can be connected, and the communication improved among them (Ozturk, 2021) (Deng & Menessa Carol C, 2021)

With the advancement in technology new and better systems were built and the usage of AI and IoT increased. Earlier BIM was being used for the 3D modelling of buildings and connected to IoT real time visualizations were being used to predict the future and support decision-making but with the advancement in AI now the concept of Digital Twin has arisen. Digital twin will not only include the real time replica of the asset but in addition it will also have the ability to support control and monitoring of the environmental aspects and automated response to the physical asset according to the set strategies in the ontologies for the Digital Twins (Deng & Menessa Carol C, 2021)(Figure 9).

Digital Twin is just not beneficial for the construction phase, but its value continues during the operation phase of the buildings. The simulation and monitoring abilities help in the reduction of the energy usage (Alonso, et al., 2019).

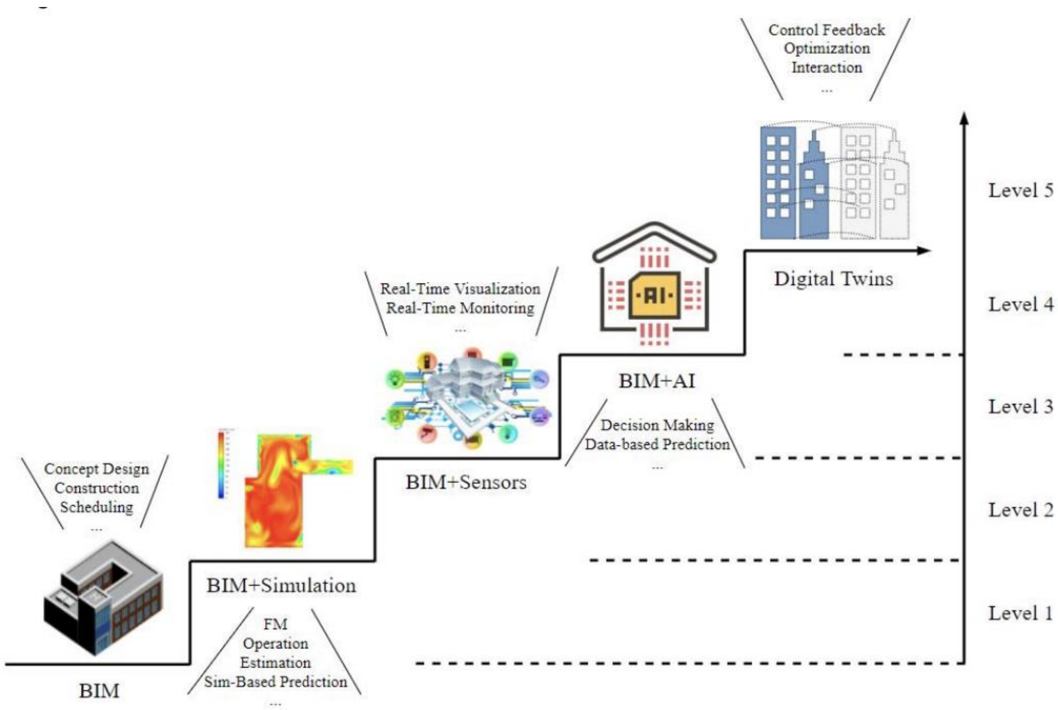

Figure 9. From BIM to Digital Twin (Deng & Menessa Carol C, 2021)

2.2.2 Digital Twin in Project Management

Studies on Digital Twin has shown that it has been helpful on different aspects of project management explained as. (Brilakis & Hans Fischer, 2019)(Figure 10)

- Facilities management and Operation
  Digital twin can help in facilities management for small and large scale. Sensors can be used to record the usage of the facility and then that can be used to optimise environmental conditions. This improves the living experience and at the same time helps in reducing costs.

- Asset condition and monitoring
  Digital twins can be used to monitor the asset throughout its life and the data can be compared to evaluate the condition using visual/ digital models. This can help in maintenance suggestions and furthermore the predictive maintenance operations can be utilized to prevent possible problems and avoid risks.

- Sustainable development and Decision-making

  By the help of Digital Twin abilities sustainable future can be developed by making the decisions leading to desired results. In projects if the desired sustainable goals are set and the Digital Twin is built according to those standards then it provides the solutions to reach the desired outcome.

Figure 10. Digital Twin for Project Management

2.2.3 Digital Twin Characteristics

Digital Twin consists of three main components namely physical asset, virtual replica, and data connecting the two. These main three parts make up the Digital Twin. The physical asset is the object that is present in the real world or example (buildings, hospitals, schools etc.). Virtual replica is the 3D model of the physical asset that is being updated in real time by means of the data that is collected from the physical object and connected to the virtual replica. Key Characteristics from Building Industrial Digital Twin are listed by Nath, (2021) in **Table 5**. The data is analyzed and simulated in the virtual model to find out all the possible outcomes in different scenarios to make the best choice for the real system. Digital Twin is referred to as a key enabler for digitalization or digital transformation for the organizations (Yan, et al., 2022). This process of data connection between real and virtual systems and the simulations are done using ontologies.

Table 5. Characteristics of Digital Twin adopted from Nath, (2021)

Characteristic	Description
Physical Entity	“An entity is an item that has recognizably distinct existence, e.g., a person, a device, a subsystem, or a group of such items”
Physical Environment	The real-world environment that the Physical Twin exist in (factory, oil platform, hospital, nature reserve, etc.)
Virtual Entity	The virtual Digital Twin prototype and instance synchronized with the physical entity at a twinning rate.
Virtual Environment	The technology-based environment that the virtual Twin exists in.
Synchronization (Twinning)	Updating the state of the physical twin and virtual twin.
Twinning rate	The rate or frequency at which synchronization happens.
State	The values of all the parameters of both the physical and virtual twins in its environment.
Physical to Virtual connection	The communications and data connections or processes used to establish this synchronization of the state at the prescribed twinning rate.
Physical processes	The processes in the real-world environment that change or impact the state of the physical twin.
Virtual processes	The processes in the virtual environment (such as analytics or mathematical calculations) that predict the change or impact on the physical entity.

2.2.4 Digital Twin Capabilities

According to (Boje, et al., 2020) the Digital Twin abilities can be stated as sensing, simulating, learning, predicting, optimising, and end user engagement. These can be explained as

- **Sensing**: sensing is the ability to observe the physical world with the help of sensors. As AI is used in this process so the sensing can be for different factors example: air quality, energy consumption, lighting, climate control etc. It can be used to measure any change in the physical asset.

- **Simulating**: the ability to sync data from the physical world and the ontology model with the virtual model for that asset. Whatever changes are sensed they are synchronized to the virtual model or twin for processing.

- **Learning**: it is the ability to store data, facts about the asset continuously and process it for the designed DT purpose.

- **Predicting:** it is the ability to process the data and predict all the possible behaviours of the physical asset. So, it provides all the options of a situation.

- **Optimising:** it is the ability to recommend the smart allocation of resources dynamically for the physical asset.

- **End-user Engagement**: it is the ability to keep all the stakeholders informed and up to date on all the changes happening (Boje, et al., 2020).

All these abilities can be utilized in all the fields specially in the AECO-FM industry. These abilities if properly used can help improve many processes of the construction industry such as sustainable development of the buildings, smart supply chain, risk management, cost management, effective decision-making (Ozturk, 2021). Digital Twin is a platform where all the organization, team members, stakeholders are on the same page. The same information is always available to everyone and continuously being updated. This feature makes it special when it comes to decision-making.

The digital Twin can be categorized into three sections as “what is, what if, and how to”. The “what is” is the observe part where the system observes a change using it’s sensing ability. The “what if” part is the anticipate section of the system where it uses simulating, learning, predicting, and optimizing abilities to gather data, generation and evaluation of possibilities and finding the best optimal option. The “how to” part is the implement section where the best solution selected is implemented and end user engagement is also utilized. This is visually shown in the research framework (Morvan & Serres, 2022) (Figure 12).

The digital transformation is taking over all the industries. This brings many opportunities for the businesses but there is a need to integrate the digital technology, information, and the decision-making process to address specific business challenges (Yan, et al., 2022). This can be done utilizing the digital twin system, as DT connects the information and the asset. The main functions of Digital Twin can be summarized as prediction, safety, and diagnosis (Kunath & Winkler, 2018)

Hu and co authors (2021) have stated the present day challenges faced by the development and adoption of Digital Twins. They have grouped them as five main challenges. High-fidelity modelling meaning to build a virtual replica with precision throughout the lifecycle is valuable but challenging; Data acquisition and processing meaning collection, storage and processing of data of huge amounts coming in from multiple sources is challenging; Real time connection between the physical and virtual entities meaning the networks required for the flow of data from multiple sources and its integration is challenging; unified development of platdforms and tools meaning different formats and standards cannot be interconnected so standardization is required for seamless integration which is challenging to acieve; and envronmental coupling technologies meaning coupling of external environmental considtions affecting the asset for accurate predictive analysis is challenging.

2.2.5 Digital Twin for decision-making

The importance of Digital Twin is measured in terms of the value addition, may it be to the business or to the society. The value addition for the business is the increase in the profit and for the society it can be measured in terms of lower carbon emissions and less resource wastage for construction projects considering sustainability (Agostinelli, et al., 2021; Alonso, et al., 2019; Boje, et al., 202; Kor, et al., 2021).

As the complexities increase in the fast-growing economy and businesses with a high pace, it is becoming even more challenging for the executives to make the right decisions in this uncertain environment. To help them in this situation Digital Twin plays its role in providing them with all the required reliable information and scenarios to make the perfect decisions for their businesses. Digital Twin can run simulations and predict energy consumption and help in reducing carbon emissions and costs. The energy storage and supply can be maintained with Digital Twin and help in the reduction of wastage and costs. The already built structures can be simulated with DT to improve energy efficiency (Agostinelli, et al., 2021).

It provides them with the certainty to succeed in the uncertain environment. Data driven AI such as machine learning solutions are combined with decision models to develop Simulation digital Twins. These Digital Twin's assist decision-making at every level of an organization from operational to strategic. Decision intelligence tools based on Digital Twin are the future of the organizations that want to excel in growth, digitalization, and efficiency (Morvan & Serres, 2022)(Figure 11). The information that the DT collects and utilizes is the replacement for wasted physical resources. By using simulations and analysing scenarios we become aware of the emergent behaviour of the asset. Hence, we can optimize the use of resources in the physical execution (Grieves & Vickers, 2017). The three things that add and bring value for any business. Digital Twin helps in decision-making at tactical level by preventing the possible failures as it possesses the ability to predict fore-coming bottle necks and arrange workflows according to the changing environments (Pan & Zhang, 2021).

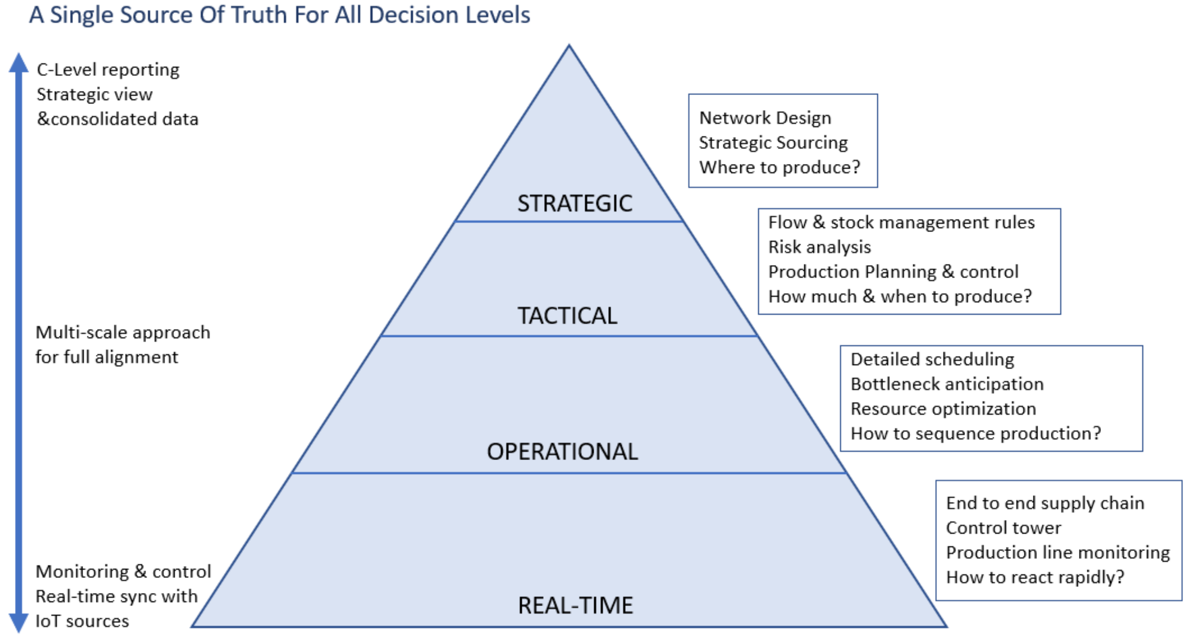

Figure 11. Digital Twin for decision-making adopted from Morvan, (2022)

Decision-making is always affected by uncertainty and lack of information, and information overload and cognitive biases also effect decision-making processes (Acciarini, et al., 2021). Knowledge visualization and Digital Twin systems can help managers by providing a complete picture of the scenario and help them in making better decisions for efficient and sustainable future in the longer run (J.Teece, 2018). The DT utilizes data driven services that are based on diagnosis and predictive functions and thus support decision-making (Jürg, et al., 2021).

The traditional 7 step decision making process can be greatly simplified to three step process by the adoption of Digital Twin (Jürg, et al., 2021). The steps 2-6 can be performed by using the abilities of DT by running live simulations for all the possible alternative options and their consequences.

Digital Twin can also consider the external and environmental factors using its sensor ability this makes it different from the present-day BIM.

2.3 Research Framework

From literature review a framework (Figure 12) was developed for the data collection from the interviews. The framework represents Digital Twin abilities and functions and the decision-making process. The framework shows the Digital Twin process based on its capabilities that can be divided into three phases namely observe, anticipate, and implement and the data driven decision-making process consisting of seven steps. This research framework was developed to find a relation and connect these two processes.

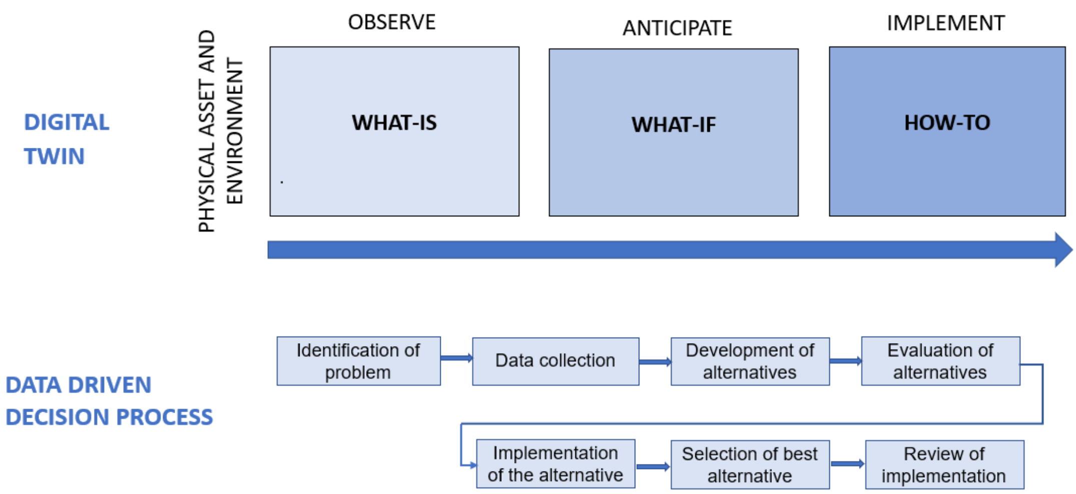

Figure 12. Research Framework

3. RESEARCH METHODOLOGY

This chapter explains the research methodology and how it was executed in detail (Figure 13). The objective of this research was to explore the qualitative relationships between the Digital Twin and sustainability through project decision-making. For this purpose, two research questions were devised and after doing the literature review, a research framework was developed for data collection as in section 2.3.

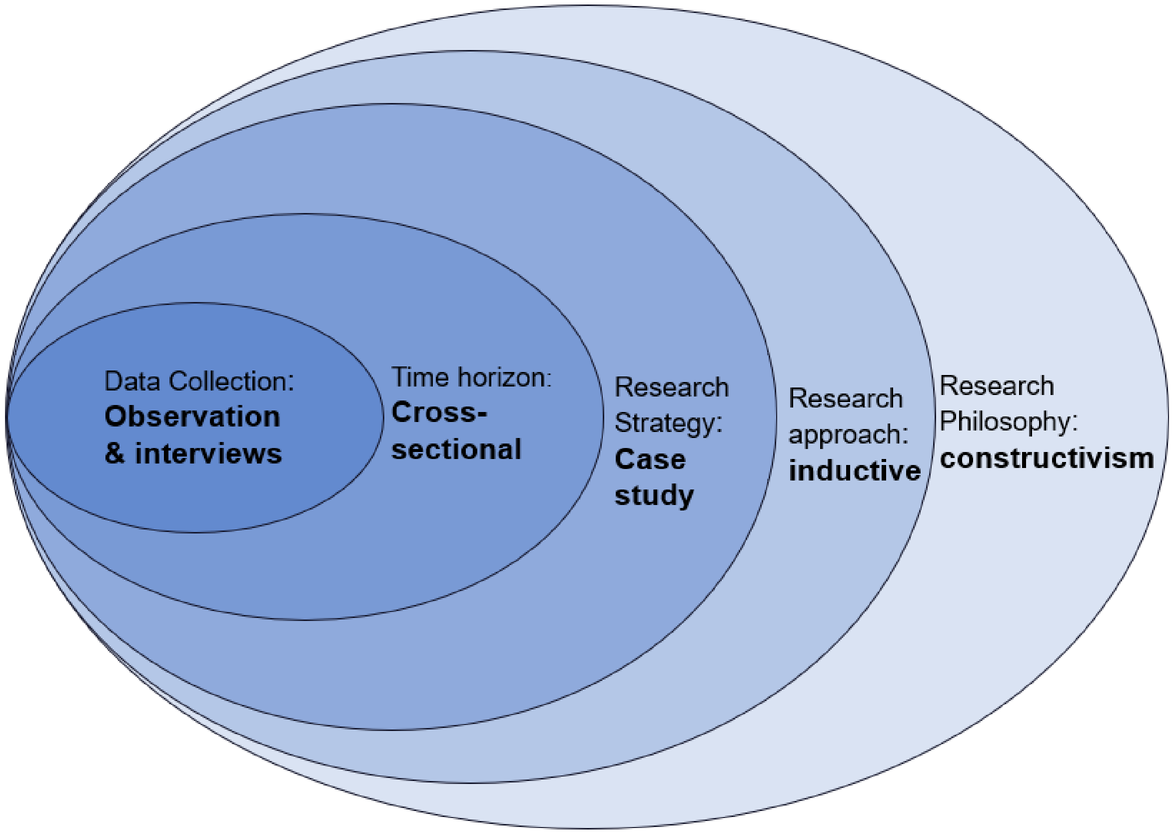

Figure 13. Research Methodology

This qualitative research was conducted with constructivism approach. The aim of constructivism is to *"distill a consensus construction that is more informed and sophisticated than any of the predecessor constructions"* (Denzin, et al., 1998). As the research topic is very novice, exploratory research was best suited. Therefore, the inductive case study approach was adopted. An inductive analysis is a bottom- to- top approach which is used to organize raw textual data into a brief format to establish links between research objectives and findings (Figure 14). An inductive approach is usually used for qualitative data analysis. It starts with observation and builds its way up to patterns and theory (R.Thomas, 2006).

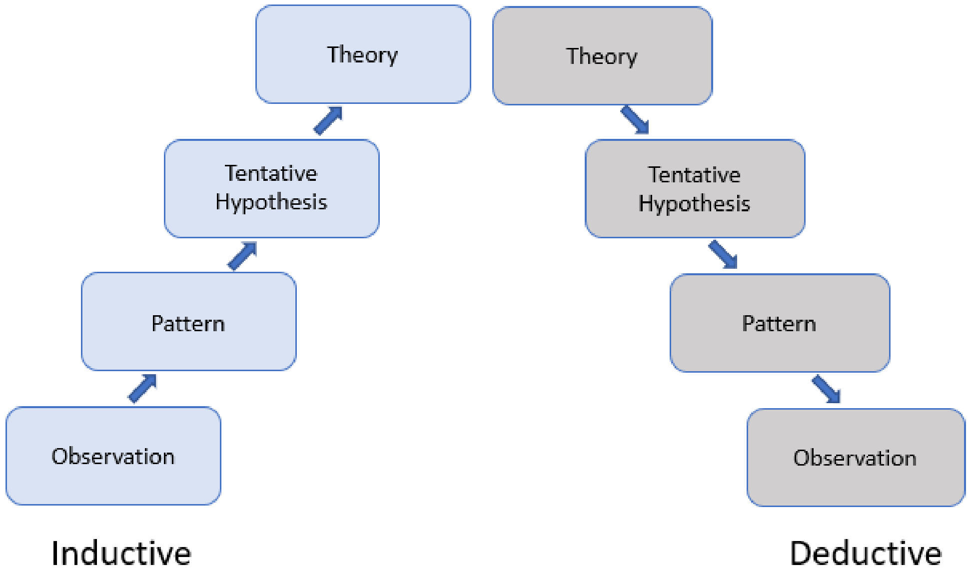

Figure 14. Inductive vs Deductive Research

3.1 Background of Case Companies

3.1.1 Case Company-1 (CC1)

Case Company-1 is a global engineering, architecture, and consultancy company founded in Denmark in the 1940's. Today it operates across 35 countries. They combine deep local insight and experience with a global knowledge base to create sustainable societies and drive positive change for the clients. They call it: Bright Ideas. Sustainable change.

16,500 experts are at the heart of its operations, helping drive sustainable impact. They deliver standalone and multidisciplinary solutions across Buildings, Transport, Energy, Environment & Health, Water, Management Consulting and Architecture & Landscape. It is a member of the UN Global

Compact, and its business contributes significantly to progress of Sustainable Development Goals.

Strategy of *CC-1* for 2025 is ‘The Partner for Sustainable Change’ which includes the four themes decarbonisation, resilience, resource management and circularity, and biodiversity.

3.1.2 Case Company-2 (CC2)

Established in the 1960’s, *Case Company-2* is a group of companies operating in the real estate and construction sector which is wholly owned by its employees. Their key goal is to make properties more functional and smarter and to improve human well-being in the built environment. their main lines of business include MEP design, property management services and software, energy, environmental and real estate sector consulting, construction management and supervision and building management.

Vision of *CC-2*: “Towards a sustainable and smart future, together. As a responsible operator in the real estate and construction sector, we want to contribute to mitigating climate change and supporting sustainable growth. We strongly believe that this can be achieved with new digital solutions and by working together with our customers and stakeholders.”

3.2 Data Collection

Data was collected from the case companies through primary and secondary sources as shown in Table 6**.** Primarily data was collected through semi-structured interviews. The questions for the interview were constructed keeping the role and designation of the interviewee in mind, secondly according to the ongoing discussion. Secondary data was collected from exploring the files, presentations, reports, and web sites of the case companies. Different sources were used to establish the credibility of the data collected for research. Specific project reports were identified and studied thoroughly to analyze the findings.

Table 6. Data Collection

Data Source	Category
World Wide Web of the case company	Secondary
Case company reports about the digital transformation	Secondary
Case company reports on future development	Secondary
Semi-structured interviews	Primary

Case Companies were selected on the basis of industry and the use of digital technologies related to the research. Three case companies were selected and were contacted via e-mail. Two companies responded and agreed to be interviewed. The interviewees were selected on the basis of their roles related to the Digital Twins and availability. Five interviews were conducted. The list of the interviewees is in Table 7.

The interviews were conducted online through Teams meetings. The interviews were recorded with permission from the interviewees. Before the interviews, a brief introduction of the research and research framework was sent to the interviewees to get better answers related to the topic. The questions asked during the interviews were constructed keeping the research framework as shown in **Error! Reference source not found.** in mind. The questions were about the digital tools being used in the projects and their level of maturity, phases of the projects in which they were being utilized and their impact on the decision-making process. Each interview lasted for an hour on average.

With a constructivist approach each interview continued in investigating the relations in more detail. The interviews were transcribed using the Teams software and then each interview was crosschecked for mistakes manually by listening to the interviews and comparing it to the text.

The interviews were read many times to identify the patterns and relations between the data and literature review which led to the general findings and discussion.

Table 7. Interviewee Details

Case Company	Interviewee	Years of experience in AECO-FM industry projects	Date of the interview	Designation
CC-1	**Interviewee A**	12 yrs.	09.03.2023	Head of Sustainability, Building Services
	Interviewee B	2 yrs.	10.03.20023	HVAC Project Manager
CC-2	**Interviewee C**	35 yrs.	29.03.2023	Regional Manager, Europe
	Interviewee D	25 yrs.	05.04.2023	Development Director (Technologies)
	Interviewee E	12 yrs.	13.04.2023	Director, Digital Business Design

4. RESEARCH FINDINGS

The Digital Twin is a concept that has been around for more than two decades, but its adoption has gained momentum during the last few years. DT is perceived very differently by different professionals. Some consider it more of data and others more as advanced visualization. From the gathered data and the literature, we can say that DT is a model where data coming from different sources and nature is combined in a common environment which can be represented visually depending on the use case. A project manager from Case Comapany-1considers DT as *"it's basically still numbers, the goal would be if we could implement that into like IFC model or digital 3D model to visualize the data."* (Interviewee B). While a director from *CC-2* is of the view that *"When we are talking about digital twins the graphics is a minor thing, more interesting thing is the ontologies and databases and how they are communicating together"* **(**Interviewee D). Another manager from *CC-2* considers DT as *"Where we have kind of models, and we have a dynamic data and static data in the same system."* (Interviewee C).

The maturity of Digital Twins in the practical field is at different levels and the organizations are continuously developing it further. Even if the maturity is not high, the companies are still investing in the development of Digital Twins because of the value addition it brings for business as well as society. Using the DT in case projects 30% better performance was achieved by reducing the emissions with the same cost level utilizing the abilities of simulations and computational design. *Case Company-1* has delivered a negative operational carbon emissions project operating on 100% renewable energy utilizing digital Twin technology. *Case Company-2* has managed to reduce annual energy costs by 6% in five years, which amount to 3.5 million euros.

The technology seems ahead of time for the clients as they are not accepting it as anticipated, only the early adopters are acquiring it while the majority is still waiting to see the additional value DT has to offer from use cases. *CC-2* representatives said that *"the market is not ready yet, it seems that they don't believe in the possibilities…"* (Interviewee C) And that *"But still, I think we are* *too much ahead of time"* (Interviewee D). The development and adoption are taking a long time. People are acknowledging the benefits of DT but continuing to work in the old ways. A director from *CC-2* showed his concerns about this *"my worry is that we are staying too much on the early stages that we are not maturing to something."* (Interviewee E)

The Digital Twin can be used from the start of the project till the closure of the project but in practice different companies are utilizing it at different phases of the project. The case companies have focused on utilizing Digital Twins for the facility management phase, for optimizing operations, and are now also considering developing it further for the design and planning and construction phases of the project. As the future is data driven and in the AECO-FM industry the data created through the design and planning of the project is valuable and can be used to create added value during the facility management of the buildings. The experts are of the same view that they should make *"better use of building information models to make a life cycle assessment calculation"* (Interviewee E) and that to *"utilize data from the BIM side to the performance management side."* (Interviewee A)

There is a lot of information that is created during the design and construction of buildings and there is a loss of information when the building starts operating due to breaks and fragmentation of the process. So, to utilize the created information during the operations of the building the Digital Twins were created. The director from *CC-2* explained *"The intention was how we can use that information that is created during design and construction in the operations of the buildings"* (Interviewee E). Before the use of DT, the operators of the building used to start from scratch. They had to gather the information about the assets and conditions manually and keep records in maintenance books.

Based on the findings the following table has been developed to explain project phases, decisions involved, process of decision with the Digital Twin and its benefits (Table 8). Due to limited time, the researcher was able to conduct interviews only related to the facility management and design phase of the projects. Because the case companies are not presently working on DT in the construction phase, so that is an opportunity for future research. They plan to expand the scope of DT to other phases of the project as well in the future.

The common challenges for the adoption of the Digital Twin in the case companies were observed to be the common data environments, unified platforms, and standardization of systems. The case companies are working on developing CDE and have achieved some success in this but developing a common platform is still a challenge. The industry is also working on developing some standards and for this purpose alliances have been formed. Data acquisitions and processing is being done smoothly and is not seen as a challenge. Real time data is also being gathered using the sensors, and IoT's and processed without any issues. Data security is not seen as a challenge by the case companies.

Table 8. DT impact on project decision-making in case companies

Project Phase	Project Decisions	Process with DT in Case Companies	Highlighted Benefits of DT by the Interviewees
Design & Planning	• Cost estimation • Carbon emissions • LCA	• The requirements set the goals to be achieved. • The system simulates options of the best recipe to achieve set goals of Carbon emissions. • The system calculates the costs. • Provides predictive analysis. • Provides simulated options for better decisions.	• The automated system is faster and makes the process faster and efficient saving time required for decisions. • supports decision-making by improving efficiency and reducing biases. • abilities such as simulations and prediction present with best possible solution. • Data based rational decisions. • Continuous monitoring from real time data coming from sensors and IoT for energy conservation. • Different visual representations for specific use case and user.
Procurement	• Supplier selection • Construction logistics		
Construction	• Site monitoring • Safety management • Quality control • Environmental issues.		
Maintenance	• Monitoring • Check-ups • HVAC control • Energy usage	• Problem identification as soon as the components set values go up or down. Immediate identification of a problem • Diagnosis of the problem in virtual environment. All possible alternatives analysed and best option available. • Identification of exactly what and where the problem is and what action is required.	

4.1 Digital Twin Applications

Digital Twins can be a step towards breaking the silos of the industry and bringing all the stakeholders together. Traditionally design models were divided between stakeholders of the project, and no one model was complete in terms of information. With DT the data can be gathered in one common platform. The complete picture of CDE can be seen in Figure 15. *CC-1* has started working on DT with this mindset of Common Data Environment, *"…in the common data environment this could be just done in the platform"* (Interviewee A)***.*** *CC-2* is on the same methodology, and they also consider that having the CDE will benefit for the industry as well as the client. *"Combining information to each other, we get the digital twin and that saves money for the customer because earlier it was manual work. This gets better result at a cheaper price*." (Interviewee C)

To achieve this goal the long ongoing stereotypes of the industry need to be broken. The thinking of the individuals and the groups involved in the projects; all the stakeholders must come together to achieve the full benefits that the DT has to offer. This is the biggest hindrance that has to be crossed. The director from *CC-2* stated that *"The mentality of the silos is what is preventing that we have a common integrated Digital Twin."* (Interviewee E)

The Digital Twin helps in multi-objective optimizations, instead of the traditional process of constructing buildings and choosing one of two options, a holistic study is possible. Meaning all possible solutions are generated and the outcomes are studied to choose the best possible solution that gives the desired life cycle performance with the lowest investment cost. These studies include energy consumption, life cycle cost, carbon emissions and investment costs. *"We take the data and visualize that in a platform of business intelligence data environment and select solutions that are the combinations that give the best life cycle performance with the lowest investment cost."* (Interviewee A)*.* Another project manager from *CC-1* also thinks *"the point is to help the energy systems get optimized and help the owner get the most money wise"* (Interviewee B).

The DT can automize the processes and connect the phases of the project. By doing so a lot of time will be saved. AECO-FM industry has been known for cost and time overruns. The cost estimations for the project is a tedious job and is usually not very accurate, when the project actually goes into the construction phase, there are many cost overruns due to wrong estimations so this problem can also be solved using DT. The decisions involved during the tendering and selection of the contractors and sub-contractors take a long period of time and becomes one of the reasons of delay of the projects. These processes can be automized using DT as stated by the head from *CC-1 "…the process could give the calculated costs and automatically followed by the tendering process"* (Interviewee A).

The Digital Twins are the central repository of data that can be visualized and presented in 3D views depending on the use case. The visualizations help in understanding and utilizing the technology by the layman as well. The maintenance person at the facility can also use the system if it provides them the information in a visual way, they can zoom in the part that needs repairs or maintenance and see what needs to be done. Data can be hard to understand but pictures speak a hundred words. As stated by a project manager from *CC-1 "it would be easier to use even for someone that's not deep inside that system."* (Interviewee B).

DT is equally beneficial for renovation projects as for new construction projects. In renovation projects usually there are no existing digital models and records of the assets. So, laser scanning can be done easily to get all the data in one place and know the exact conditions of the asset. It gives the added value of cost and time saving as compared to the traditional process of manually compiling the lists of the asset and its condition. Then this data can be further utilized to conduct the renovation.

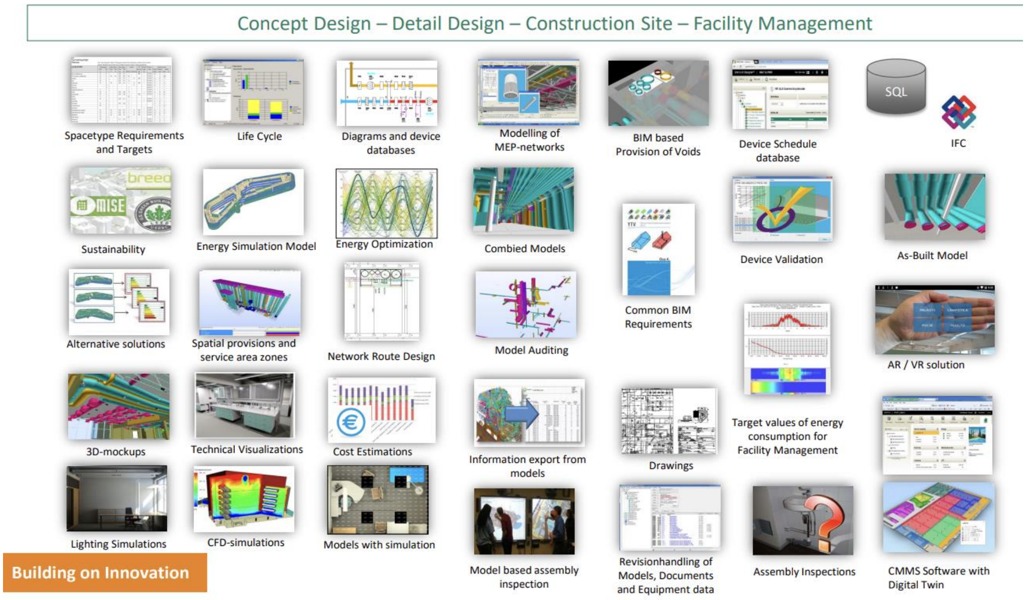

Figure 15. Data through Project phases in DT (Case Company secondary source)

4.2 Decision-making in Case Projects

Decisions are made during every phase of the project and on daily basis, but decisions related to set the pathway of the project may it be cost, time or scope are made during the planning and designing phases of the project which are of utmost important for any project. *"The early phase of the designing is the essence part because the decisions are made in there and then after detailed design phase, we are just following because every decision is already made."* (Interviewee D)**.** *"The decisions start when you start to look at what do I want? that's where big decisions are made…"* (Interviewee C).

DT helps the experts from the very start by providing the options and scenarios for the given conditions. When there is a set requirement of carbon footprint and energy consumption then the designer can explore the possibilities in the virtual environment that to achieve the set goals which materials should be used and in which combinations. What will be most optimal solution for the given problem. As explained by the head from *CC-1 "You can build like a recipe that if I change this then this changes this as well during the building* *design and that's something that we are currently working on…"* (Interviewee A).

The main criterion of decision-making is KPI based like in every other industry. Parameters like cost, energy consumption, carbon emissions, maintenance costs, and capital investment. When asked that what is the main criteria for decision-making the common answer by all the experts was *"Cost, off-course."* So, we cannot ignore this criterion even for the value addition DT has to offer. The industry must find a balance between the cost and benefits to achieve the adoptability of the technology that is the future.

Decisions made during the design phase of the projects take long time. Traditionally the designer will specify the specifications, but he cannot specify a single product, because the client and the contractor always look for the cheapest product. So, the contractor proposes the machinery, and the designers approves. The final decision ais always of the client. And this process is usually made through e-mails and consumes a lot of time. But in Digital Twins this can be done in the system and the models will be up to date with the actual information.

"The contractor would put the data in the platform and the designer would just select it and then the data would go back to the simulations and so on and back to the BIM model as it is." (Interviewee A).

Traditionally during the construction phase the specified products are changed to a cheaper option and no one is informed, and the information models are never updated so the data models have the old information and the asset built has different components. When there is need for maintenance and replacement then the maintenance team has to manually make reports of the actual assets and then the process for maintenance starts. But with Digital Twins and use of software specifically designed for this purpose helps in overcoming this problem. The asset managers keep a track of the assets, and all the products are updated regularly. And if the construction manager wants to change the specified product, he has to make a change request that is approved by the owner and the project manager. *"…use it also for the asset* *approval, if construction manager wants to change a unit to a cheaper model and then he can make a change request…"* (Interviewee C).

Decisions in the AECO-FM industry has faced this challenge of being subjective rather than objective. Traditionally the personal experience of the expert was depended upon for the decisions and that also included the cognitive biases making the decisions non-optimal and irrational but with the use of digital technologies like DT this is remediable (Figure 16). DT ability of transforming data into usable information for decision-making is of significant value. *"it's not anymore about the expertise or the historical background of the designer rather the information that is there…"* (Interviewee A). For decisions to be data-driven and objective the quality of the data is very important. *"The quality of the data has to be good, has to be trustworthy and reliable so that decisions can be based on it."* (Interviewee E). and added that *"Rules and standards that would really help to make data-driven decisions."* (Interviewee E).

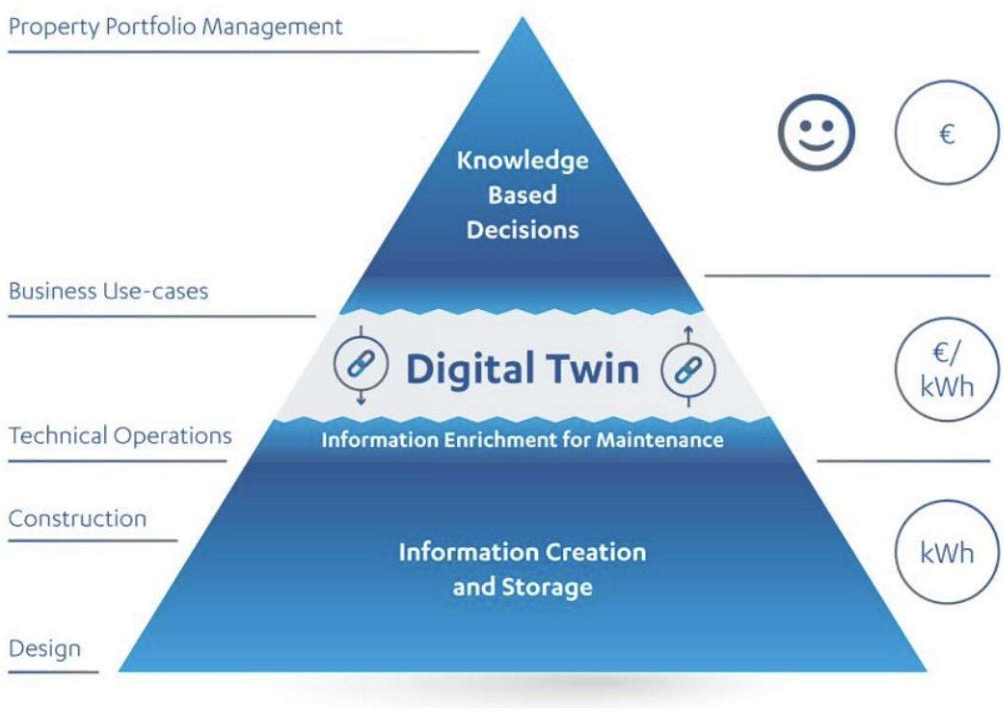

Figure 16. Data-driven Decisions (Case Company secondary source)

To optimize the decisions data-driven rational approach is used. Simulations are run to calculate the energy consumption and Carbon emissions and to achieve that goal how much insulation is required and what should be the wall thickness, glazing ratio and so on. And the decisions are made according to the simulations (Figure 17). *"…doing those simulations to optimize the design and to make sure that it's according to the set goals…"* (Interviewee A). The project environment is everchanging and so *"the data energy cost and everything is varying. The simulations give a holistic understanding that what should be done and why."* (Interviewee A). Project manager at *CC-1* explains *"…we simulate the system with real time data, the simulation gives us the optimal way that it should have worked, and then we compare it, how did it actually worked…*we can help the system work more optimally.*"* (Interviewee B).

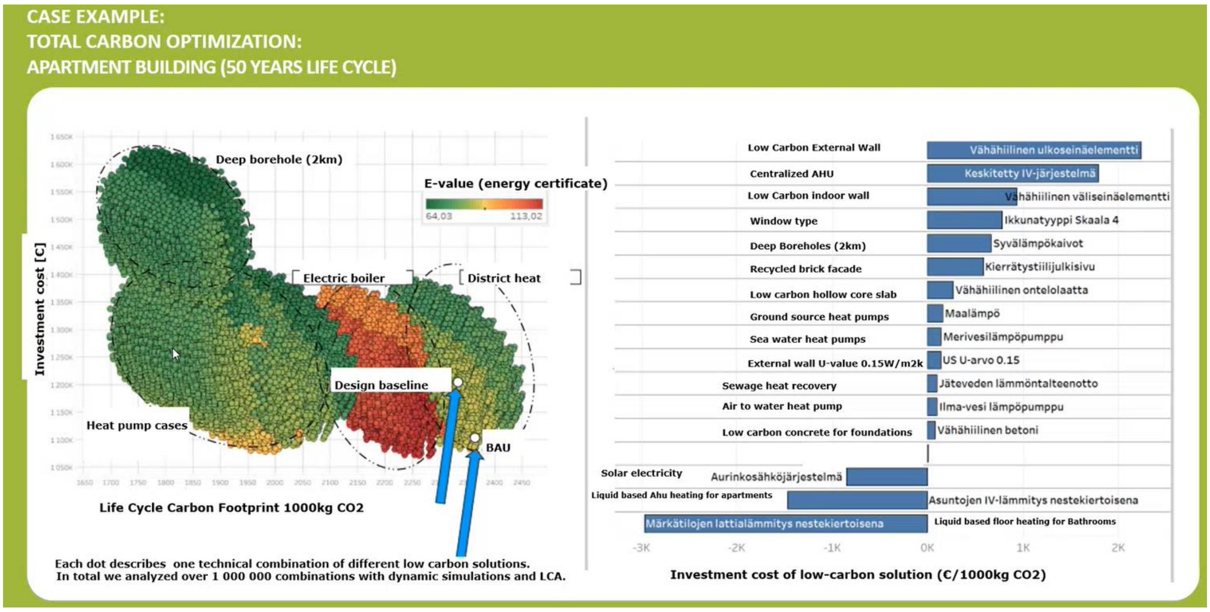

Figure 17. Simulations for Carbon emissions LCA (Case Company secondary source)

DT helps the clients/owners in making the right decisions at the right time by providing the overall picture of their assets and comparison graphs to understand the present situation and optimize their decisions for the future. As explained by the director at *CC-2 "…gathering information from portfolio of the* *buildings and get the results like diagrams or power BI reports… that is meaningful for the building owner."* (Interviewee D)**.** Project Manager at *CC-1* explained *"we process the data and make reports for the building owner that how is the system working and what kind of revenue is it giving money wise."* (Interviewee B).

Digital Twins added value to decision-making is that it brings transparency to the process and the way it is visualized is the main thing. Before decisions made were not clear that why a decision was made and how was it justified but with Digital Twins the system makes all the information available to everyone. Every decision is recorded and can be reviewed, making the process of decision-making very transparent. DT brings different sources of information together to speed up the decision-making process.

Digital Twin can calculate the need for repairs and renovation with the data coming in from the assets. The condition of the asset is measured by comparing its performance over time and future needs re predicted. If the asset's efficiency is reducing, then the system can predict when a repair would be needed, and a ticket is generated. This saves a lot of time and cost. *"… to calculate what are the kind of repair needs for the future."* (Interviewee C).

The real time dynamic data is collected using sensors and IoT's that is linked to the BMS and the IFC models. This helps to analyse the dynamic and the static data together and control and monitor the assets. Conditions like the temperatures, air humidity, CO2 levels etc. the Digital Twin collects all this data and connects it to the 3-D IFC model in the user interface. It is very easy to navigate through the asset and monitor the asset equipment (Figure 18). The static data is also available, so the set values and conditions are also visible in the model meaning the set values at which the systems should be working are in the static data.

The actual real time values are continuously being updated and as soon as some values goes up or down from the set values the system generates a warning that the maintenance person can check and sort. If some system like a fan, cooling or heating unit is not working and the effected space related to that unit is visible in the Digital Twin system and the maintenance person knows exactly where to go and what unit to fix. It saves a lot of time and money.

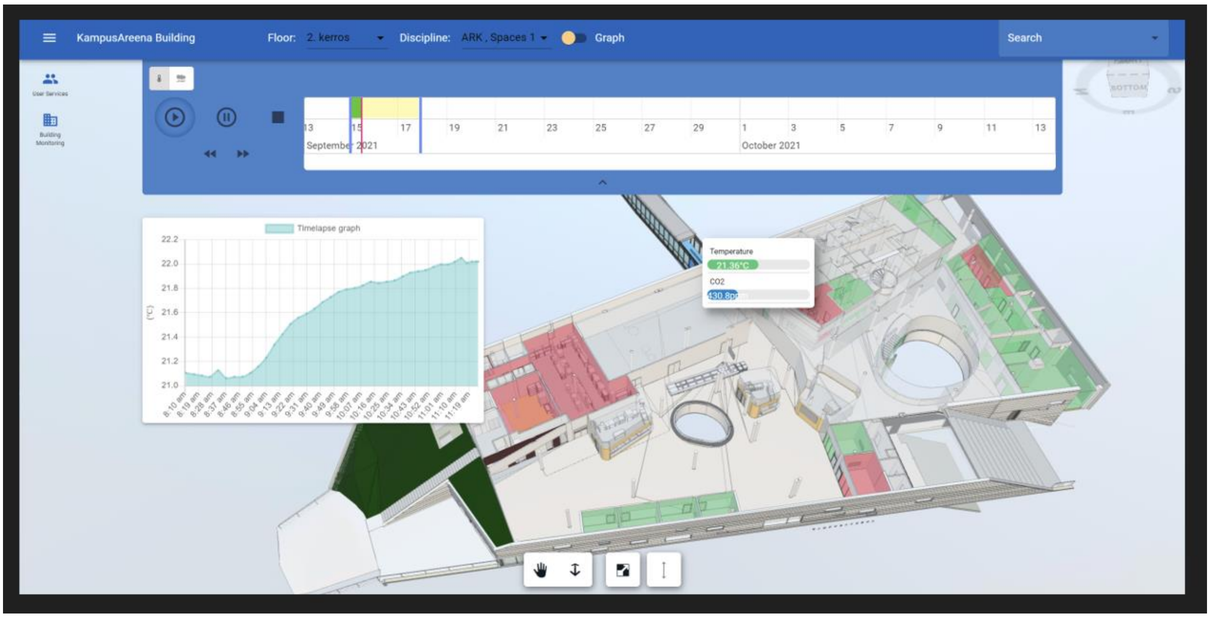

Figure 18. Digital Twin Interface (Case Company secondary source)

The DT system has a user interface for the facility management team. This interface is continuously monitoring the assets. The dynamic data coming from the assets is being updated in the system and is being saved as well. So, the data history is being build up with the actual physical building. This data is very useful and serves as a reference when making decisions for new projects as well. The new estimates can be compared to the historical data and analysis can be done how to make better choices in the future.

User feedback and interaction is also part of the DT as the humans using the facility are the most important part. Their wellbeing and satisfaction are of utmost important. The users can leave their feedback in the system about the temperatures, air quality and comfort level of the space. And if some problem is reported it can be checked from the DT that what were the temperatures, CO2 levels, air humidity etc. at the time of use of a specific space and the values can be adjusted (Figure 19).

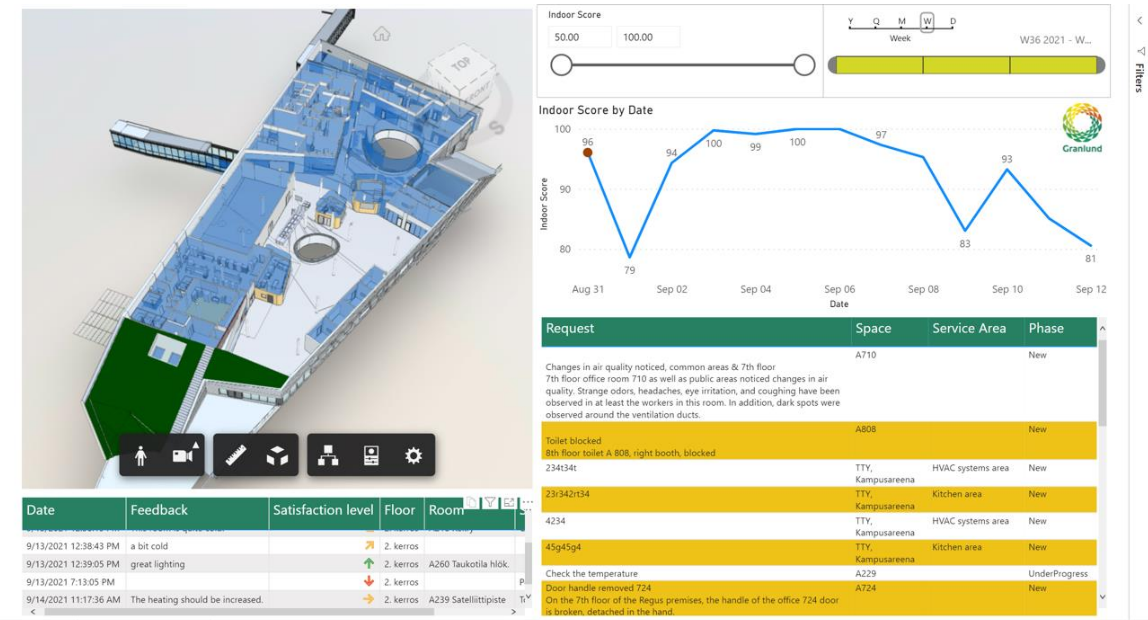

Figure 19. Ticket for an issue in DT (Case Company secondary source)

The DT helps in decision-making for facility management at operational, tactical, and strategic levels. When you compare the portfolios of similar buildings with specific benchmark then you can make decisions at strategic level if a certain building is lower or higher than the benchmark. Another strategic example can be when you analyse spaces you see which spaces are occupied and which are never occupied so those spaces can be put to some other use. When you analyse spaces for property owners to lease the property, which property to lease and when to lease these analysis help in such decisions at tactical level. As you go into detail at the specific building components and compare them for operations then you make decisions at operational level.

4.3 Sustainability in Projects of Case Company

In the recent years sustainability has gained consideration in the early stages of projects, doing the estimates for the carbon footprints and the material selection based on having least impact on the environment but it's becoming more and more important day by day. The ESG requirements must be followed and LCA has also taken off. But considering sustainability during the operations phase of the buildings in something new *"…importance in the last years on sustainability thinking more about when the building is operating"* (Interviewee E). Operation phase that contributes to the CO2 emissions during the operation of the building considering the lifespan of the building 30-50 years. Software's like One Click LCA are very helpful in such calculations.

DT can help in reaching sustainability goals as the old data from previous projects can be utilized to learn the shortcomings and make better decisions in the future. According to one project manager at *CC-1 "It can be used later when designing a new building, to see how this building worked and what could be done better."* (Interviewee B). A director from *CC- 2* said ***"…****to make use of that information from previous projects make a rough estimation of what could be the carbon footprint in the very early stages before even modelling something."* (Interviewee E).

The research shows that the DT provides a platform for a data-driven lifecycle of continuously increasing knowledge and data, leading to informed decision-making. The ability of DT to cover the entire lifecycle of a building allows circular construction. This data-driven approach of DT makes it different and better from the traditional BIM models.

4.4 Updated Research Framework

In light of the findings the research framework was developed further that shows the relation between Digital Twin and Data driven decision-making (Figure 20). The seven steps of data-driven decision-making process and the process of Digital Twin "observe", "anticipate" and "implement" have been related to each other.

Observe: first step of the decision-making process, that is identification of the problem is done by the what-is part of the Digital Twin by the sensors and real time data coming from the physical asset and the real time monitoring. As soon as the components efficiency drops the system sets an alarm. So, the process being automized identifies the problem automatically.

Anticipate: the second to fifth step of the decision process that are data collection, development of alternatives, evaluation of alternatives, and selection of best alternatives is performed by the Digital Twin in the what-if by collecting the required information from the sensors and systems to develop the possibilities and run simulations for them. And present the outcomes of the options in visual representations providing the optimal solution in that scenario.

Implement: the sixth and seventh step of the decision-making process implementation of the alternative and review of the implementation is done in the “how-to” part of the Digital Twin. Here AI helps in automizing the system so it can implement the selected solution to the physical asset wherever possible. And after the implementation the outcomes are monitored and reviewed for the future.

The maturity of the systems in the Case Companies varies. They are developing and implementing the abilities and functions of Digital Twin according to the projects and specific use cases. As the CDE and standard platforms are not available, the implementation of Digital Twins to its fullest capabilities and potential is still not possible. But it is helping the Case Companies in improving efficiency, cutting costs, saving energy and time, and reducing carbon emissions.

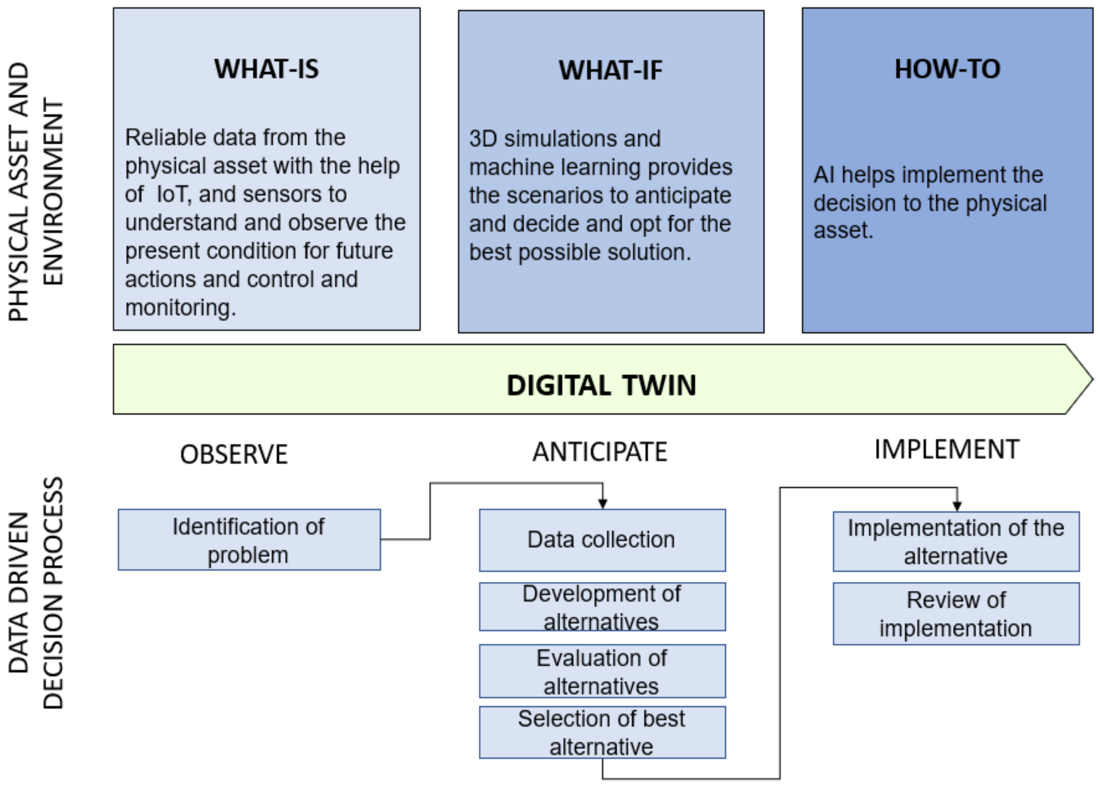

Figure 20. Research Framework of DT for Decision-making process

5. DISCUSSIONS

In this chapter the research findings will be related to the literature review and further possible avenues for research will be identified. The chapter will discuss the shortcomings of the AECO-FM industry regarding the project decisions and how DT has influenced the subject. Further it will explain and relate the findings for added value that DT brings for projects with regards to sustainability. Lastly the proposed research framework under section 1.4 will be analyzed with the research findings.

The findings state that the DT concept is ahead of its time, what that means in practice is that the clients and owners are not ready to invest in it. They have their concerns regarding the costs and gained value. They require more use cases that can prove to them that the value DT will bring is real and much more than what is expected. This is one of the challenges for the adoption of DT in the AECO-FM industry. The literature also talks about this challenge of fragmentation and financial limitations of the industry to slow the pace of digitalization (Nahyan, et al., 2019).

According to the findings from the interviews and literature review, the fragmentation of data is a common issue in the industry due to the differences in methods and implementation, resulting in delays in meeting project budget and timeline. Cost and time overruns are common in the construction industry (Nahyan, et al., 2019) (Poon & Price, 1999).

5.1 Digital Twin to Support Project Decision-making

RQ 1. How Digital Twin implementation supports project decision-making?

To get the answer for this research question the data collected was gone through to compile the findings as in Chapter 4. Then those findings were compared to the literature review to see where the industry stands in practice and what can be done in the future.

One of the problems of the AECO-FM is subjective decision-making. The experts, project managers, construction managers are known to be taking decisions based on their intuition and experience rather than taking informed, rational, and objective decisions. There are many reasons leading to this shortcoming, one of them being time pressure and lack of reliable and up to date information. In the literature Poon & Price, (1999), Ksiazek, et al.(2015), Kunath & Winkler, (2018) and Killen, (2017) all have indicated this problem and have suggested digital tools to overcome this problem. From the research findings we have also established this fact that DT has helped the AECO-FM industry to overcome this problem by providing the experts with the required, reliable information for the decisions. As was stated by a head: *“it's not anymore about the expertise or the historical background of the designer rather the information that is there…”* (Interviewee A). For the data to be reliable and up-to-date, the case companies have developed or are working on developing Common Data Environments. The CDE is the basic requirement, the primary driver and value creator for the DT concept.

In section 4.1 we have found that the case companies are utilising Digital Twin abilities to take a step towards breaking the silos of the industry. The industry has realized the need to bring all the stakeholders together. The added value DT will bring is understood by the experts and therefore, the adaptation is being developed. As we have established from the literature that with the help of DT, an integrated system all the different stakeholders can be connected, and the communication improved among them (Ozturk, 2021, Deng & Menessa Carol C, 2021). The improved communication will save time and availability of the information required for making informed decisions. Even at the low maturity of the DT the benefits are seen and achieved that paves the way to develop further so that the true potential of this digitalization tool can be achieved.

DT not only helps in bringing the stakeholders together it but also helps in overcoming the data loss at the handovers at different project phases. This is an important step towards breaking the silos of the industry. The case companies are facing this challenge while implementing DT. To overcome this barrier, they have started to bring in the experts of the next phases of the project early on. As was stated by the director at CC-2: *“We want to bring the* *people who will operate the building early on the early stages of the design."* (Interviewee E). To achieve this the case companies are utilizing integrated project delivery or alliance contracts.

The CDE or the integration of processes and data management leads to value on all levels. By having access to historical data better analyses can be done and better decisions can be made throughout the building lifecycle. Through the data-driven aspect of DT and predictive analyses, it enables better strategic decision-making. Literature also emphasizes on leveraging the data produced during the construction projects for impactful decision-making purposes (Jürg, et al., 2021).

The research found that visualization helps in understanding the current situation better as compared to excel sheets and word reports. When there is a visual representation of the numbers that shows comparisons in the form of visual graphs, then there is less chance of misunderstanding and cognitive biases when it comes to decision-making. Experts have the facts and figures in front of you. The DT provides visual representations of the KPI's set and thus, decision-making becomes more data based and rational. As explained in the literature that knowledge visualizations help in reducing cognitive biases due to complexity and uncertainty and helps in decision-making by Acciarini, et al. (2021), Secundo, et al .(2022), and Killen & Kjaer, (2012).

The decisions to be taken by the clients take a long time and a lot of emails have to be exchanged to get the approvals in the traditional way of working. So, the decision making is not data driven and rational but solely based in the biases and the information that is present at that time may it be inadequate. While the DT makes this process data driven reducing the biases and making the process as rational as possible. And the use of DT even does the seven-step process in three steps meaning it takes less time and is more reliable (Jürg, et al., 2021).

5.2 Digital Twins and Sustainability

RQ 2. How Digital Twin helps to achieve sustainability goals through project decision-making?

To get the answer to this research question the findings were seen through the sustainability point of view to get general results.

The DT utilized at the facility management phase of the construction projects by the case companies has proven successful in reaching towards the set goals of energy savings and cost reductions. By making informed decisions the companies have been able to cut short carbon emissions and energy consumption and investment costs. The literature also states that the value addition for the business is the increase in the profit and for the society it can be measured in terms of lower carbon emissions and less resource wastage for construction projects considering sustainability (Boje, et al., 2020) (Kor, et al., 2021) (Alonso, et al., 2019) (Agostinelli, et al., 2021) (Säynäjoki, et al., 2011).

Sustainability has gained importance in the last few years with the issue of global warming. Earlier the carbon emissions were considered during the design phase of the project but recently life cycle assessment has gained popularity and has become a requirement for the construction industry. The ESG rules and regulations have made sure that the environmental factor of sustainability is not neglected or overlooked. The clients and the owners of the buildings and even the occupants/ users of the buildings are becoming more aware of these issues. The clients are setting clear requirements about the carbon emissions and energy consumption.

DT helps the designers to come up with the best possible solution to achieve the requirements of the client, be it low carbon emissions, low energy consumption or limiting waste material during construction phase. Furthermore, in the future DT can improve safety standards on the construction sites. It can be studied for the development of virtual trainings of the workers.

The DT concept enables access to a continuous data flow throughout the building lifecycle starting from the very planning of the project and as it has been stated by the experts from the case companies, the most important and impactful decisions are made at that stage. The real time data and predictive abilities of the DT helps the designers and managers to follow the data-driven decision-making process and make informed, optimal and rational decisions. This sets the way towards sustainable smart construction from the early stage of the projects. The implementation of AI and IoT can enhance the industry's overall performance with respect to sustainability.

At this time of digitalization and digital transformation the companies in the AECO-FM sector must make the right choices and that too at the right time to be able to catch up with the technological advancements. To accomplish this the case companies have made strategic decisions to develop the DT concept. The DT provides businesses with the certainty in the uncertain environment. From the data collected in the interviews we see that there is a lot of investment being done on the innovation department of the case companies. They are continuously working and developing the products to achieve better results and to satisfy the clients with their specific needs.

In summary, the Digital Twin supports project decision-making by providing the required information needed for the decisions, doing the analysis of the possible alternatives, and providing the most optimal solution all in one place and in much less time than traditional methods. So, we can say DT supports decision-making by improving efficiency and reducing biases. Utilizing the simulation and prediction abilities of the Digital Twin helps to take decisions that result in reducing carbon emissions and energy consumption for the life cycle of the assets.

6. CONCLUSION AND LIMITATIONS

6.1 Conclusion

The study shows that the maturity level of the DT is still in its early phase in the AECO-FM sector but even at low maturity, the case companies are achieving value and they are continuously developing Digital Twins. The AECO-FM industry is still under the influence of silos and fragmentation. DT can help to overcome this issue but for it to happen, all the parties involved need to work together and develop common work procedures and data management platform.

The limited search data collection shows that decisions in projects are also siloed. It takes a lot of emails and information exchange until a decision is made. This can be solved using Digital Twins in design and planning phases of the projects as is being done in the operational phase of the project. The problem of subjective decisions in the AECO-FM industry can be resolved using the DT concept. DT will ensure required data availability for rational and data-driven decision-making.

DT helps save time during the decision-making process by making the information available and its predictive analysis capability helps in choosing the best possible option in less time than traditional methods. The Digital Twin helps in multi-objective optimizations, meaning instead of choosing one of two options, a more holistic study is possible.

DT and its capabilities are helping case companies reach their sustainability goals and cutting carbon emissions. DT helps in improving efficiency of the AECO-FM sector by making decision-making process data-driven and rational.

6.2 Limitations and Recommendations for Future Research

Data was collected for this research through five interviews and two case companies. The research data was limited due to time constraint and also due to the fact that the DT concept is quite new in the industry, and it is in the development phase. The findings being valid are limited to the projects executed by the case companies. The AECO-FM sector has the challenge of developing common platforms and standardization to pave the way for the adoption of Digital Twins. However, the current maturity is in its early stages and there are considerable opportunities ahead.

For future research the developed framework can be tested in other phases of the construction project with larger case data. Other factors affecting decision-making can also be studied, such as role of decision makers. This was a qualitative study in the future a quantitative study can be done to analyze the relationships.

As it is established in the research that the AECO-FM industry is siloed, future research can also be done on how the Digital Twin helps in defragmentation of the AECO-FM industry?

REFERENCES

Acciarini, C., Brunetta, F. & Boccardelli, P., 2021. Cognitive biases and decision-making strategies in times of change: a systematic literature review. *Management Decisions,* 59(3), pp. 638-652.

Agostinelli, S., Cumo, F., Guidi, G. & Tomazzoli, C., 2021. Cyber-Physical Systems Improving Building Energy Management: Digital Twin and Artificial Intelligence. *Energies MDPI,* 2338(14).

Alonso, R. et al., 2019. SPHERE: BIM Digital Twin Platform. *Proceedings MDPI.*

BIM frameowrk, T. B., 2020. *The BIM frameowrk Blog.* [Online] Available at: https://www.bimframework.info/2013/12/project-lifecycle-phases.html.
[Accessed 30 January 2023].

Boje, C., Guerriero, A. & Rezgui, S. K. a. Y., 2020. Towards a semantic Construction Digital Twin: Directions for future research. *Automation in Construction,* p. 114.

Bokhari, S. A. A. & Myeong, S., 2022. Use of Artificial Intelligence in Smart Cities for Smart Decision-Making: A Social Innovation Perspective. *Sustainability,* 14(2).

Brilakis, I. & Hans Fischer, F. S., 2019. *Built Environment Digital Twinning,* Munich, Germany: s.n.

Citroen & L., C., 2011. The role of information in strategic decision-making. *International Journal of Information Management,* pp. 493-501.

Deng, M. & Menessa Carol C, K. V. R., 2021. From BIM to Digital TWins: A Systematc Review of The Evolution of Intelligent Building Representations In the AEC_FM Industry. *Journal of Information Technology in Construction,* Volume 26, pp. 58-83.

Denzin, K., N. & Lincoln, Y. S., 1998. The Landscape of Qualitative Research: Theories and Issues.. *Thousand Oaks.*

Edwards, W., 1954. The theory of decision making.. *Psychological bulletin,* 51(4), p. 380.

Erdogan, S. A., Šaparauskas, J. & Turskis, Z., 2017. Decision Making in Construction Management: AHP and Expert Choice Approach. *Procedia Engineering,* Volume 172, pp. 270-276.

Everett, R., 2009. The Building Colleges for the future Progra. Delivering a Green and Intelligent Building Agenda. *NEw Review of Information Networking,* pp. 3-20.

Grieves, M. & Vickers, J., 2017. Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems. *Transdisciplinary perspectives on complex systems: New findings and approaches,* pp. 85-113.

Harrison, F. E., 1996. A process perspective on strategic decisoin making. *Management Decision,* 34(1), pp. 46-53.

Hu, W. et al., 2021. Digital Twin: a state-of-the-srt reviiew of its enabling technologies, applications and challenges. *Journal of Intelligent Manufacturing and Special Equipment,* 2(1), pp. 1-34.

Hwang, B.-G. & Ng, W. J., 2013. Project management knowledge and skills for green construction: Overcoming challenges. *International Journal of Project Management,* Volume 31, pp. 272-284.

J.Teece, D., 2018. Dynamic Capabilities as (workable)management systems theory. *Journal of Management and Organization,* 24(3), pp. 359-368.

Jürg, M. et al., 2021. Digital Twin-Enabled Decision Support Services in Industrial Ecosystems. *Applied Scieences,* Volume 11, p. 23:11418.

Kerzner, H., 2013. *Project Managemnet A systems Approach to Planning, Scheduling, and Controlling.* 11 ed. New York: Wiley.

Khakheli, M. & Morchiladze, G., 2015. Factors Affecting Decision Making In an Organization. *International Journal of Management and Commerce Innovations,* 3(1), pp. 425-428.

Killen, C. P., 2017. Managing Portfolio interdepencies: the Effects of visual data representations on project portfolio decision making.. *International Journal of Managing Projects in Business,* 10(4), pp. 856-879.

Killen, C. P., Geraldi, J. & Kock, A., 2020. The role of decision makers' use of visualizations in project portfolio decision making. *International Journal of Project Mnagement,* Volume 38, pp. 267-277.

Killen, C. P. & Kjaer, C., 2012. UNderstanding project interdependencies: The role of visual representation,culture and process. *International Journal Of Project Management,* pp. 554-566.

Kirytopoulos, K., Voulgaridou, D. & Voulgaridou, V., 2010. *Too many cooks spoil the broth, or maybe not?.* Milan, PMI.

Kor, M., Yitmen, I. & Alizadehsalehi, S., 2021. An investigation for integration of deep learning and digital twins towards Construction 4.0. *Smart and Sustainable Built Environment,* Volume ahead of print.

Kritzinger, W. et al., 2018. *Digital Twin in manufacturing: A categorical literature review and classification.* Vienna, IFAC Papers On Line, pp. 1016-1022.

Ksiazek, M. V. et al., 2015. Computer-Aided Decision-making In Construction Project Development. *Journal of Civil Engineering and Management,* 21(2), pp. 248-259.

Kunath, M. & Winkler, H., 2018. Integrating the Digital Twin of the manufacturing system into a decision support system for improving the order management process. *Procedia CIRP,* Volume 72, pp. 225-231.

Le, P. L., Elmughrabi, W., Dao, T. M. & Chabaane, A., 2018. *Decision-making in Construction Logistics and Supply Chain Management: Evolution and Future Directions.* Lyon, France, ILS Conference.

Morvan, M. & Serres, J., 2022. *Simulation Digital Twins.* [Online] Available at: https://www.digitaltwinconsortium.org/ [Accessed January 2023].

Müller, R., 2009. Cultural differences in decision making in projects teams. *International Journal of Managing Projects in Business,* 2(1), pp. 70-93.

Nahyan, M. T. A., Sohal, A., Hawas, Y. & Fildes, B., 2019. Communication, coordination, decision-making and knowledge-sharing: a case study in construction management. *JOURNAL OF KNOWLEDGE MANAGEMENT,* 23(9), pp. 1764-1781.

Nath, S. V., Schalkwyk, P. v. & Isaacs, D., 2021. *Building Industrial Digital Twins.* Birmingham: Packt Publishing Ltd..

Nwogugu, M., 2005. Towards multi-factor models of decision making and risk. A critique of Prospect Theory and related approaches, part I. *The Journal of Risk Finance,* 6(2), pp. 150-162.

Oliveira, A., 2007. A Discussion of Rational and Psychological Decision-Making Theories And models: The Search for a Cultural-Ethical Decision_Making Model. *Electronic Journal of Business Ethics and Organization Studies,* 12(2).

Ozturk, G. B., 2021. Digital Twin Research in the AECO-FM Industry. *Journal of Building Engineering.*

Pan, Y. & Zhang, L., 2021. A BIM-data mining integrated digital twin framework for advanced project management. *Automation in construction,* Volume 124, p. 103564.

Pearce, A. R., Bernhardt, K. L. S. & Garvin, M. J., 2010. *Sustainability And Socio-Enviro-Technical Systems: Modeling Total Cost Of Ownership In Capital Facilities.* s.l., s.n.

Poon, S. & Price, A., 1999. Decisions made on Construction Sites. *Association of Researchers in Construction Management,* Volume 2, pp. 589-594.

Powell, T. C., Lovallo, D. & Fox, C. R., 2011. Behavioral Strategy. *Strategic Management Journal,* Volume 32, p. 1369–1386.

R.Thomas, D., 2006. A General Inductive Approach for Analyzing Qualitative Evaluation Data. *American Journal of Evaluation,* 27(2), pp. 237-246.

Säynäjoki, A., Heinonen, J. & Junnila, S., 2011. Carbon Footprint Assessment of a Residential Development Project. *International Journal of Enviromental Science and Development,* 2(2), pp. 116-123.

Secundo, G., Giannluca, E., Alessandro, M. & Karl-Heinz, L., 2022. Strategic decision making in project management: a knowledge visualization framework. *Management Decision,* pp. 1159-1181.

Shahzad, M., Shafiq, M. T., Douglas, D. & Kassem, M., 2022. Digital Twins in Built Environments: An Investigation of the Characteristics, Applications, and Challenges. *Buildings,* 12(120).

Silvius, A. G., Kampinga, M., Paniagua, S. & Mooi, H., 2017. Considering sustainability in project management decision making; An investigation using Q-methodology. *International Journal of Project Management,* pp. 1133-1150.

Simon, H. A., 1979. Rational Decision Making in Business Organizations. *The American Economic Reveiw,* 69(4), pp. 493-513.

Singh, H., 2015. *Project Management Analytics: A Data-Driven Approach to Making Rational and Effective Project Decisions.* New Jersey(California): Pearson Education, Inc..

Stingl, V. & Geraldi, J., 2017. Errors, lies and misunderstandings: Systematic review on behavioural decision making in projects. *International Journal of Project Management ,* Volume 35, pp. 121-135.

Szafranko, E., 2017. *Decision problems in management of construction projects.* s.l., IOP publishing, p. 251.

Verhoef, P. C. et al., 2021. Digital transformation: A multidisciplinary reflection and research agenda. *Journal of Business Research,* pp. 889-901.

Weck, M., Humala, I., Tamminen, P. & Ferreira, F. A., 2022. Knowledge management visualisation in regional innovation system collaborative decision-making. *Management Decision,* pp. 1017-1038.

Yang, R. J., Wang, Y. & Jin, X.-H., 2014. Stakeholders' Attributes, Behaviors, and Decision-Making Strategies in Construction Projects: Importance and Correlations in Practice. *Project Management Journal,* 45(3), pp. 74-90.

Yan, M.-R., Hong, L.-Y. & Warren, K., 2022. Integrated knowledge visualization and the enterprise digital twin system for supporting strategic managemnet decision. *Management Decision,* 60(4), pp. 1095-1115.